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Comprehensive Optimization Strategy of Traffic Signal Control System

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Abstract:

Traffic jams have become a worldwide presence where urban centers are concerned, and it is clearly seen that traditional fixed-time control systems are not as flexible. The systems fail to have some ability to react to real-time traffic conditions, situations that bring a lot of inefficiencies, more fuel consumption, and more emissions. This paper forwards a new data-driven traffic signal control optimization technique, which deploys historical data analysis and real-time adaptive control. Supplying historical traffic pattern data, the presented system estimates traffic volume and makes use of intelligent signal control plans that advocate for movable vehicles and clean lungs. Dynamic control allows the system to adapt by managing the signal via real-time live traffic conditions.

Key words: Traffic signal control; adaptive control; historical data analysis; discrete control.

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1. Introduction

Traffic flow is an unprecedented problem posed by urbanization nowadays. Cities ranging from New York to Tokyo suffer the traffic congestion, which not only creates socio-economic and environmental problems during a long period but also is connected with the world whole over. The population density rise in urban areas is resulting in increased traffic congestion, which in turn worsens overall pollution problem, extends traffic times, and decreases people‘s quality of life. Road traffic modeling and improvement (intelligent solution), which has a direct effect on fuel consumption and growing concerns on the greenhouse gases emissions, has become a subject of scientific research and engineering [1, 2].

Related articles have shown that traffic actuated control based on time, where signal timings are preset based on estimation, is the most prominent traditional traffic signaling. Such variables do well for the less extensive networks of predictable traffic; they do not suit the modern urban environments‘ highly adjustable and fluctuating traffic conditions [3]. Where traffic engineering matured in cities, traffic control defects became more apparent as cities expanded, traffic volumes equally grew, and transportation networks became more complex.

The incorporation of Intelligent Transportation Systems (ITS) in traffic management systems is a significant development. ITS embraces a multitude of technologies and gap-filling processes with the motive of achieving safer, efficient, and greener transportation systems. A key feature of ITS is the real-time collection and analysis of traffic data, which is vital for decision making, such as adaptive signal control [4, 5].

This paper describes a comprehensive traffic signal control optimization strategy comprising of three elements: analyzing historic data, real-time adaptive control, PID discrete controller. In the upcoming sections, we are going to discuss the importance of the components, their adoption in different urban settings, and the effect they have on traffic flow effectiveness.

2. Methodology

2.1 Data-Driven Decision Making

In this day and age, data is negatively perceived as undesirable, but it should serve as the basis for decision-making processes in virtually any industry, including traffic management. Traffic control systems are now required to process massive volumes of data equipped from sensors, cameras, GPS devices, and vehicle-to-infrastructure (V2I) communication networks to be intelligent in selecting the appropriate amount of time for traffic signals [6, 7]. The presence of historical traffic data in the process of analysis is the key to getting a better understanding of the future vehicular trends and the dynamics of flow.

Analyzing the historical traffic data allows transportation engineers to come up with smarter and more effective signal timing schemes based on peak hour fractions, weekend and weekday congestion, and regular bottlenecks. As a consequence of detecting these patterns, traffic control devices can modify the standard operating procedures of the traffic signal systems during recognized traffic system fluctuations. In such cases, some intersections may be legionary crowded in the evening rush hour, meaning that traffic lights for lanes with higher levels of traffic could be longer when compared to traffic lights for the opposite lanes [8].

A study carried out in Los Angeles, California, revealed that historical data is paramount for the optimization of traffic signals. Traffic engineers examined a series of peak-period traffic data from intersections of the entire city for several years. By using such information, they have created new timing strategies for the peak hours. Consequently, vehicle delays were reduced by 20% on average during peak periods, indicating that a data-driven strategy is pretty effective [9].

The analysis of the traffic situation is based on a number of key factors that are constantly changing, and data-driven decision-making allows the traffic control systems to promptly respond in such cases. Adaptive control systems provide immediate alterations to real time traffic data with regard to signal timings, reducing unnecessary stops and delays, as a result of which green light timings are continuously changing dynamically. For example, traffic situation can be very confusing when an accident happens and bottleneck appears [10]. In such a case, the traffic system may automatically change green light timings and assign priority to the vehicles in alternative routes.

2.2 Real-Time Adaptive Signal Control

2.2.1 Literature Review

Real-time adaptive traffic signal control being the likely area of future management of traffic. Unlike the current fixed time systems, the adaptive control systems collect circulating information about traffic conditions. Then, when needed, they adjust the signal timings with the goal to optimize traffic flow [11]. To optimize traffic efficacy and environmental sustainability, the target is to cut down car length of queuing and stop behind.

The central piece of the real-time adaptive control is the mean time between green changing period and the light changing positions which are based on the actual traffic conditions. The example is, if the sensors are capable of showing a grow or surge of cars in one lane, the adaptive system is able to prolong the green light for that direction automatically, so that more cars accumulate before the light turns red [12].It is this technology that observes traffic status on 24/7 basis and adjusts light timings adequately making sure that traffic congestion does not violate the proper performance level.

One implementation example of an adaptability traffic control system would be SCATS – Sydney Coordinated Adaptive Traffic System, in which traffic lights are adjusted in real-time based on traffic flow. The SCATS tool uses vehicle loops and cameras to monitor traffic volumes, and traffic signal timings of the system are adjusted based on data each few minutes to make the entire process as smooth as possible. This is also the case for London where the Split Cycle Offset Optimization Technique (SCOOT) system adjusts traffic signal timing in real-time using data from sensors for optimizing the flow [13].

Adaptive controlling now has evidence beyond cutting vehicle delays. As the systems facilitate the traffic industry to flow smoothly, they also contribute to the decrease in the costs of fuel and emissions of vehicles. Similarly, about 20% improvement in air quality was achieved after introducing adaptive signal control at one of the arterial corridors in Los Angeles, as cars delayed less time at the intersections [14]. An existence of study done in Singapore demonstrated that instant regulated management contributed to a 30 percent reduction of the travel times for the peak hours, which is a direction to improving the urban mobility system on a large scale [15].

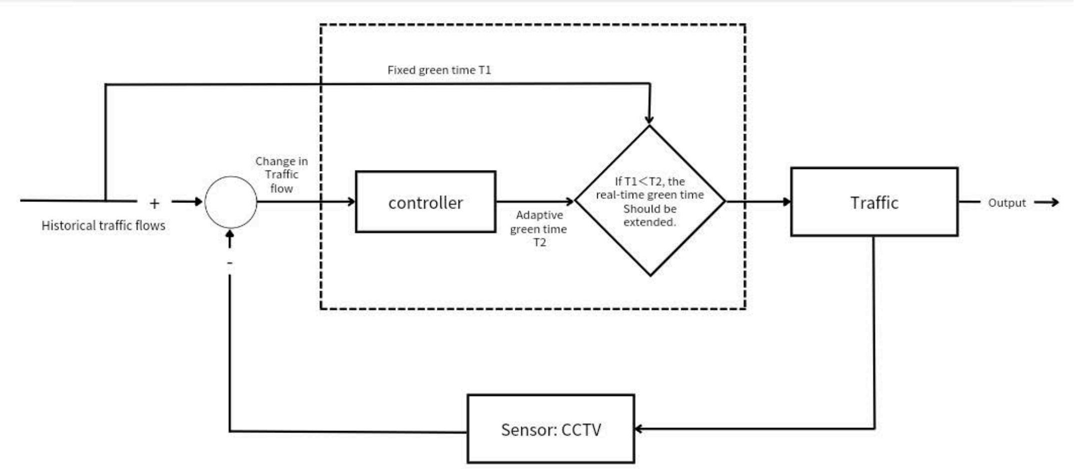

Fig. 1 Adaptive traffic control process

2.2.2 Adaptive control system Design

The control process elucidated in this study consists of processing historical traffic flow data, and its transcription into a certain hardware. The first step is the transfer of traffic data to the green light schedule of each intersection. While CCTV takes periodic snapshots of vehicles at the intersection that the YOLO system processes to count cars from those images [16], the counting is done in real-time. The vehicle count crossing from before the intersection is put as the numerator. Real-time traffic data combine with historical data to serve as the feedback for the forecasting and eventually for the planned adjustments. The controller solves the differential equations that evaluate the variable green light time with the standing pre-set times as the reference. The green light will be extended if it is required to reduce the congestion. This may take the form of the adaptive time exceeding the preset length of time. The total vehicle delay time is taken as the main performance measurement index of the control system.

Real-time adaptive control models take into account predictive modeling as essential, which enables a system to forecast traffic conditions in future based on what is available now. The formulas of discrete control system and Greenshileds' model are taken into the calculations. This model considers the volume of the traffic passing through the intersection when calculating the optimal duration for a traffic signal cycle. The formulas are as follows:

$$\mathrm{v} = v_f\,(1-\frac{\rho}{\rho_m}) \tag{1}$$

The equation's variables accrue from elements involving:

l V: Speed, which is the vehicle's traveling speed, (unit: km/h).

l Vf: Free flow speed, which is the speed a vehicle can reach to the maximum uninterrupted from other vehicles.

l ρ: Traffic density, which is the number of vehicles in unit length of road (unit: vehicles/km).

l ρm: The maximum traffic density value, which indicates that vehicle speed reaches zero due to the saturation of the traffic density.

$$\frac{\mathrm{d}^2\rho(t)}{dt^2}+2\zeta\omega_n\frac{d\rho(t)}{dt}+\omega_n^2\rho(t)=K\mu(t) \tag{2}$$

The equation's variables accrue from elements involving:

l ρ(t): traffic density,vehicles/unit distance.

l ωn: the natural frequency, which gives the rate to real traffic change in any signal,

l ζ: the damping ratio, which prevents the oscillation of traffic after intervening.

l K: the system's gain, and thus the traffic flow change driven by control inputs is expressed.

Such forecasting models are employed by adaptive traffic control systems to rethink signal timings prior to congestion occurrence.

Table 1. Data of Beijing traffic condition [17]

Area Name	Traffic Index	Congestion Level	Average Speed (km/h)
Entire Network	4.7	Mild Congestion	26.9
Inside Third Ring Road	7.8	Moderate Congestion	21.4
Between Second and Third Ring	6.9	Moderate Congestion	24.2

Between Third and Fourth Ring	5.3	Mild Congestion	28.0
Between Fourth and Fifth Ring	3.8	Basic Free Flow	30.1
Eastern City District	7.7	Moderate Congestion	19.9
Western City District	7.1	Moderate Congestion	22.1
Haidian District	3.5	Basic Free Flow	30.0
Chaoyang District	5.9	Mild Congestion	26.2
Fengtai District	2.7	Basic Free Flow	31.6
Shijingshan District	2.3	Basic Free Flow	33.6

Based on the data from table 1, all the variables are calculated. The response time is set to 12 seconds in our case. Because the response time is defined as the time from when the traffic signal changes to when the number of cars decreases. Therefore, we can assume that the response time is the driver's reaction time plus the time it takes for the car to pass through the intersection.

In the same way, the time scale is set to 3 seconds because it should be small enough to detect the dynamics of the system. In addition, the sampling frequency should be much greater than the natural frequency about ten to twenty times, because the higher sampling frequency can capture finer dynamics. Although it will increase the computational burden, it's necessary. So the sampling time is set to 0.016 seconds. The maximum simulation time is set to 15 seconds, which is five times that of the timescale. This captures the complete dynamic behavior of the system and ensures that the system response is completely stable.

2.3 Simulation and Results

According to the following passage, this part of the paper will provide the experiments done in order to confirm the proposed traffic signal optimization strategy. Ideal MATLAB simulations and Simulations in SUMO were done with samples of actual traffic data from an intersection in Beijing that were restored. Impact of the newly installed signal control system was measured by specific KPIs comprising average vehicle delay.

2.3.1 Simulation Setup

MATLAB and SUMO softwares were utilized for the simulation of urban scenarios, which are well-defined programs for the simulation of transportation systems. A mid-sized city project was chosen for this study as a case study that represents realistic city traffic conditions that vary from heavy evening traffic congestion, which occurs during rush hour, to moderate traffic flow during the typical day, to hardly any traffic during the night.

In MATLAB simulation, according to real historical data, the specifications are settled as that has an overshoot of no more than 5%, rise time from 1 to 5 seconds, settling time between 5 and 15 seconds, and a steady-state error below 1% [18].

Traffic data and sensor inputs provided real-time adjustment of signal timings in the formation of the simulated model in SUMO.

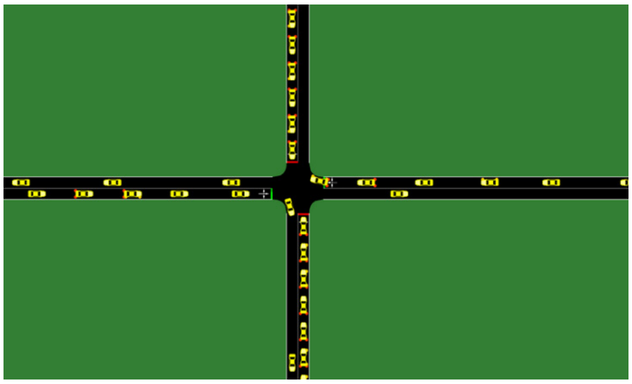

Fig. 2 SUMO intersection simulation

2.3.2 Results Overview

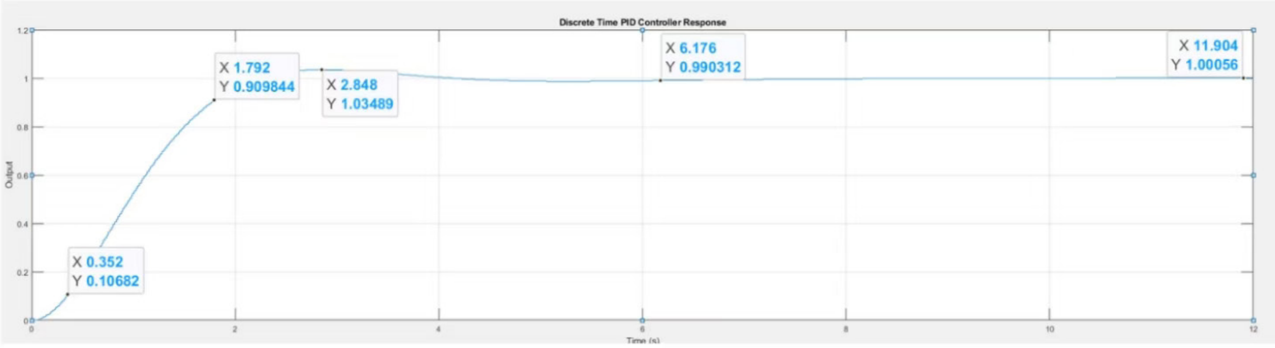

Fig. 3 Adaptive traffic control simulation in MATLAB

After applying the transfer function to the transportation system model, iterative testing identified that the system achieves optimal performance with Kp=10, Ki=2, and Kd=20. As shown in Figure 3, the step response demonstrates that the controller effectively stabilizes traffic flow within the defined parameters. The overshoot is limited to approximately 3.5%, and the steady-state error is reduced to less than 1%. Additionally, the short rise time indicates that the controller responds efficiently to fluctuations in traffic condition.

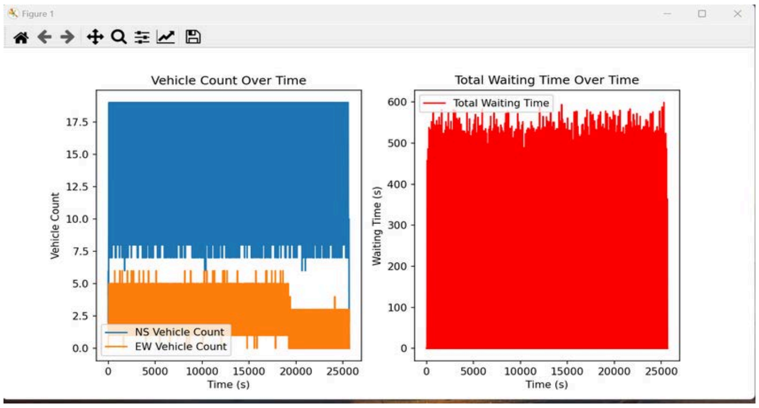

Fig. 4 Fixed-time traffic control simulation in SUMO

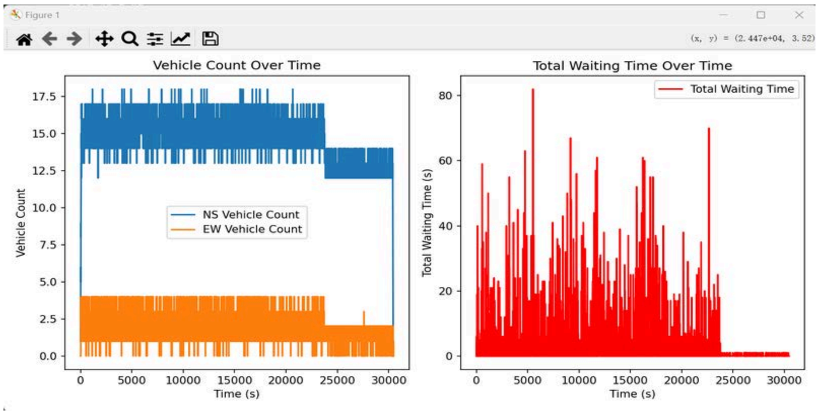

Fig. 5 Adaptive traffic control simulation in SUMO

The effectiveness of the optimized adaptive system in controlling traffic flow was apparent in the form of the decreased vehicle delay, when measured by the average delay at intersections, and fully implemented, it was during peak hours that the average delay was decreased by 92.7% in off-peak hours. By utilizing the real-time adaptive control mechanisms to select the optimal timing for the traffic lights, the system was able to react very quickly to live, real-time traffic flow conditions, which accounted for the bulk of the positive outcome, that is making traffic congestion less severe.

2.4 Discussion

The results of this paper reflect the reduction of vehicle delay that the system's potential for application in real-life scenarios, especially in high-density urban areas, is demonstrated. On the other hand, few obstacles still need overcoming to end the phase of transformation research.

2.4.1 Scalability

Even though the simulation results may be encouraging, the biggest obstacle that stands in the way of making the current system a reality is its scalability. Urban traffic networks are characterized by high complexity, thus when one needs to scale delivering an optimized signal control to an entire metropolitan area, be assured that it will highly depend on infrastructure that consists of sensors, communication, data, and storage capabilities [19]. Moreover, the computational force needed for processing live data from different intersections in the city is one of the drawbacks.

2.4.2 Cost of Implementation

The question of whether to install an intelligent traffic control system arises as yet another major problem. Adding necessary sensor technology, communication devices, and cloud-based data storage systems can be very taxing, particularly for cities with floundering budgets. Nevertheless, lowered upfront costs due to less fuel consumed, reduced emissions, and easier traffic flow may be a possible justification for these expenses [20, 21].

2.4.3 Integration with Autonomous Vehicles

As advanced autopilots (EVs) become more popular, new traffic regulating tools will also need to account for the unique abilities of the EVs to communicate with traffic corridors. Vehicle-to-infrastructure communication refers to the possibility of communication between the traffic signals and EVs in real-time, thus, EVs could have more instant and accurate control over traffic flow. The growing number of EVs calls for considering the integration with V2I technologies already in the process of upgrading of traffic control systems as EVs can offer benefits never reachable before [22].

3. Conclusion

This paper presents a comprehensive traffic signal optimization strategy that leverages historical traffic data and real-time adaptive discrete control to reduce vehicle delays. The hybrid approach demonstrated significant improvements in traffic flow when tested in simulated urban environments.

The results underscore the potential of intelligent traffic systems in addressing the growing problem of urban congestion. By utilizing discrete control, the system can continuously evolve and adapt to changing traffic conditions, ensuring that signal timings are optimized in real-time. Moreover, the integration of V2I technologies with autonomous vehicles opens up exciting possibilities for future traffic control systems.

While challenges remain, particularly in terms of scalability, cost, and privacy, the benefits of an optimized traffic signal control system far outweigh the drawbacks. As cities continue to grow, the demand for intelligent, data-driven traffic management solutions will only increase. By adopting advanced traffic control systems, urban areas can significantly reduce congestion, improve air quality, and create more sustainable transportation networks.

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