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Design and simulation of the adoptive traffic signal control system based on PID controller

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Abstract:

As the global increasement of private vehicles, the traffic congestion is getting worse, which makes a great effect on the environment and society economics. How to optimize the existing traffic signal control becomes an important part of the current research. The author finds that most current research about the traffic signal control system are focus either on improving the way of collecting traffic data, or on optimizing the control algorithms. Instead of bringing out the innovative mathematical models to improve entire system structure. Therefore, in this article, an adoptive traffic signal control system based on PID controller is designed to adjust the traffic density by collecting the real time traffic flow and change the duration of traffic signal. This research includes the following section: First model the traffic system in second order form, then the PID controller is tuned into MATLAB and simulated in the SUMO and PYTHON. Finally, the results show that the designed system can precisely control the signal duration according to the real time traffic flow. Compared to the fixed time traffic system, the total waiting time of vehicles is reduced by 84%, which greatly reduce the traffic congestion and shortens people's travel time.

Keywords: Adaptive traffic signal control, PID controller, SUMO simulation, closed loop control

1. Introduction

With the development of global economics and the increasement of people's living standard, the ownership of private vehicles is growing rapidly. The current traffic flow is beyond the original road carrying capacity, which causes the traffic congestion. This situation will trigger series problems: waste of people's travel time, consumption of automobile energy and the pollution of air [1]. A survey conducted in New York in 2020 indicates that the drivers' average waste time on traffic congestion is about 100 hours, converting to dollars at 1,486 per driver. which is an acute crisis for the society economics [2]. In addition, vehicles emit a particle called PM10. It not only pollutes the atmosphere, but also seriously harms people's respiratory system [3]. In various situations of traffic congestion, the congestion in the intersection is the most common one. Therefore, traffic signal control system in the intersection plays a crucial role in improving urban economics, air quality and human health.

The traditional traffic signal control uses the fixed time mode of operation, the system works according to the pre-input duration signal. However, this mode would lead to unsteady traffic flow, which causes traffic congestion during peak hours. Now in many cities, the traffic signal control based on the sensor measurements is widely used. Yogesh Rohilla and Dhruv Patel have designed an infrared sensor-based adoptive traffic signal control system for measuring the flow density in the intersection, setting the IR Transmitter and IR receiver at the inlet and outlet of the road respectively and upload the measured data to Arduino microcontroller board for processing [4]. Nowadays, most of the sensors are placed in the green belt or under the ground at the entrance or exit of the intersection, it only can measure when the vehicles passing by. Which causes a problem that the system unable to perceive real-time traffic conditions and rely heavily on engineers to manually adjust the signal duration under special circumstances [5]. Hua Wei et al. state that the classic strategy of traffic managers for traffic signal control is to treat it as an optimization problem based on traffic modeling [5]. In the several years' research, people tried to improve system performance by improving the way of measuring the traffic condition or optimizing traffic signal algorithms. Traditional traffic signal control relies on sensors to collect data. However, as the development of Image processing techniques and computer vision techniques, the CCTV is used in collecting data. Compared to the sensors, CCTV costs less, owns a shorter sample time and can monitor the traffic condition of the entire intersection. And at the level of algorithm optimization, a number of AI techniques with Machine learning have been proposed. Filipe Rodrigues et al. point that the application of deep learning in traffic signal control is moreover a very promising research direction at present, aiming to deal with a large number of high-dimensional states by avoiding discretization of the state space [6].

In recent years, research on traffic signal control mainly focus on the optimization of control algorithms, rather than the structure of overall system framework [7]. This article presents a Proportional-Integral-Derivative (PID) controller based close loop traffic signal control system. Which adoptively controls the signal duration by detecting real-time traffic flow and integrating the historical traffic flow in the intersection. So as to achieve the target of adjusting the traffic flow and alleviating the traffic congestion during the peak hours. The controller is simulated in a traffic intersection drawn in Sumo to judge its performance. Finally, it will provide a novel concept and approach for developing the comprehensive framework of future traffic signal control system.

2. Method

Compared to previously proposed methods such as using machine learning to optimize algorithms for traffic signal control, the use of PID controllers is simpler, less costly, and does not require large amounts of data or time for training, which can be directly applied in most cities around the world. However, there are still some challenges in using the PID controller in the field of adaptive traffic signal control, one is how to make a reasonable modeling of the traffic system, and the second is how to make the appropriate tuning of the controller to improve its performance, this study will give the solutions in the following section.

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2.1 Design the entire framework of control system

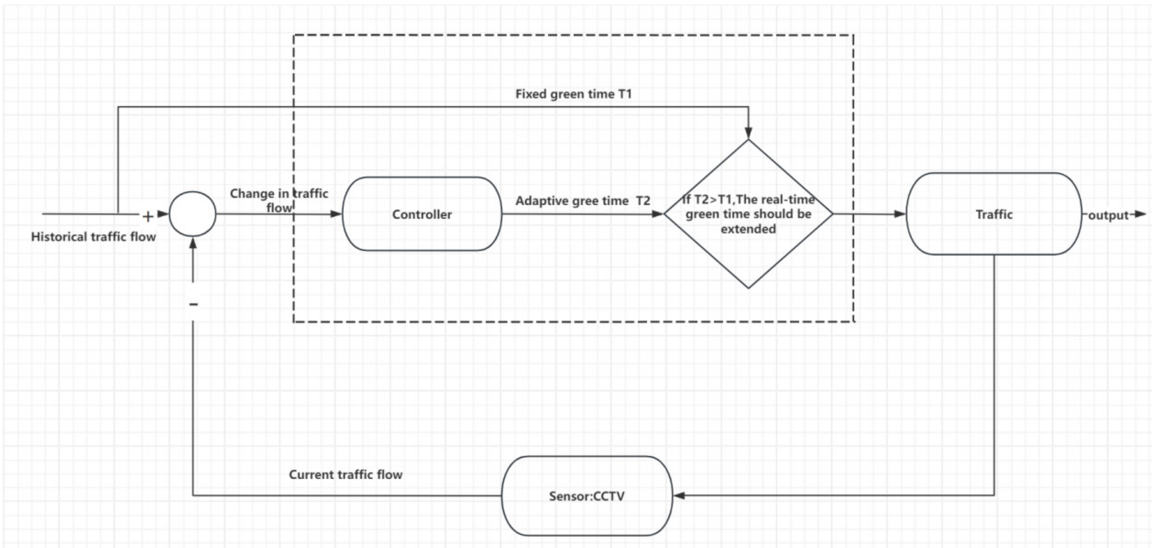

Fig. 1 Traffic system objective and Control design

As Fig.1 shows, the control process described in this study consists of processing the current changing traffic flow data and transcribing it into a PID controller to regulate the signal duration, and finally achieve the adjustment of the traffic density of the system. Closed-Circuit Television (CCTV) is first used to take a timed snapshot of the vehicles at the intersection. You Only Look Once (YOLO) is a real-time target detection algorithm that can be used to identify the size, category, and number of all vehicles in the captured road video [8]. This is a process to calculate the vehicle numbers from the snapshot, which is completed at real time. Then the traffic data is transferred to the PID controller in each intersection. The number of vehicles passing in front of the intersection is used as a control input, real-time traffic flow is combined with historical data as feedback for forecasting and eventual plan adjustments. The controller solves the differential equation for the variable green light length using a fixed time system as a reference. If there is traffic congestion in certain direction, the green light length will be extended. This will be in the form of an adaptive green light length over the fixed time green light length.

2.2 Second-order modeling and parameterization of traffic system

In the traffic system, servals variable parameters are considered:

$\rho(t)$: Traffic density in vehicles/unit distance.

$u(t)$: Phase duration of traffic signals.

ω_n: The natural frequency of a system that responds to system-specific solid-state dynamics, such as how quickly a control system responds to signal duration changes.

Based on the above variables, a second-order modeling of the traffic system at the intersection was performed:

$$\frac{d^2\rho(t)}{dt^2}+2\zeta\omega_n\frac{d\rho(t)}{dt}+\omega_n^2\rho(t)=Ku(t) \tag{1}$$

$\frac{d^2\rho(t)}{dt^2}$ and $\frac{d\rho(t)}{dt}$ represent the rate and acceleration of change in traffic density respectively. In order to make the model of traffic system closer to real life, the author make reasonable assumptions about ω_n: For designed traffic signal control system, the system response time is defined as the time between signal duration adjusts and the change in traffic density at the intersection (which can be detected by CCTV). This can be divided into the driver's reaction time and the time it takes for the vehicle to pass through the intersection. The driver's reaction time can be assumed as 2s, while the speed limit of urban intersection in China is generally 30km/h, assuming that an 80m wide intersection, the passing time is about 10s. For the step response of a PID controller, the discrete time scale is defined as the required time for output to reach 63.2%, which is usually one-fourth to one-fifth of the response time. According to the formula:

$$\omega_n=\frac{1}{\tau} \tag{2}$$

ω_n can be calculated to be 0.33 rad/s. There are serval specifications that PID controller should meet: overshoot under 5%, a rise time between 1 to 5 seconds, a settling time between 5 to 15 seconds, and ensuring the steadystate error is under 3%. t_s and ω_n are determined, the range of ζ can be calculated according to formula:

$$t_s \approx 4.6 / \zeta\omega_n \quad (3)$$

In this study, ζ = 0.8. Given that the CCTV is shot at regular time intervals, PID controller should be discretized (replacing t with kt):

$$u(k) = K_P e(k) + K_I(k) + K_D(k) \quad (4)$$

At a discrete control system, PID controller adjusts the control signal $u(k)$ to minimize the system error $e(k)$ (Difference between expected and actual values). The recursive equations of the system are obtained by using the forward difference method, bringing in the known ω_n and ζ:

$$u(k) = 2u(k-1) + 1260.032e(k) - 1250e(k-1) \quad (5)$$

The transfer function of the traffic system is

$$G(s) = \frac{\rho(s)}{u(s)} = \frac{0.1089}{s^2 + 0.528s + 0.1089} \quad (6)$$

2.3 The tuning of PID controller in MATLAB

Based on the controller specification designed above, the controller is put into Matlab for simulation. Step response is used to help qualitatively analyze the performance of PID controller. Debugging the parameters of the PID controller, and finally obtain a well-performing step response when K_P equals to 10, K_I equals to 2, K_D equal to 20, as shown in Fig. 2, which proves that the controller successfully stabilize traffic flow within the desired constraints.

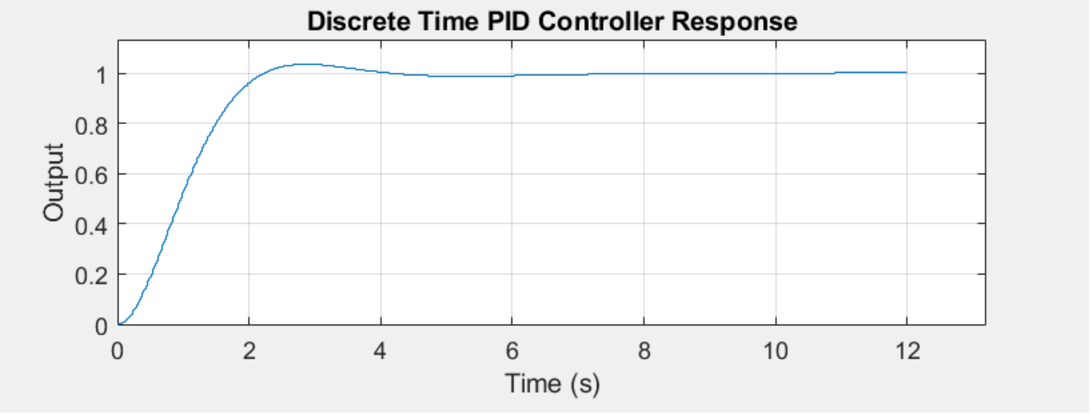

Fig. 2 Step response of Discrete time PID controller

3. Results

In order to test the performance of the designed adoptive traffic signal control system in practice, Traffic Control (TraCI) interface is used for dynamic simulation interaction between python and sumo. TraCI, which is used to implement real-time monitoring and control of simulation variables, including roadway information, signal phasing and traffic flow [9]. A simple traffic intersection used as the simulation object. The sample codes used are shown below:

pid_ns = PIDController(kp=10, ki=2, kd=20, setpoint=84)
pid_ew = PIDController(kp=10, ki=2, kd=20, setpoint=84)

Firstly two PID controllers are used to control traffic flow in north-south and east-west directions, setting the target traffic flow to 84.

min_phase_duration = 10
max_phase_duration = 60
yellow_duration = 3

The minimum and maximum durations of the phases are set and a yellow transition duration is added to prevent the traffic flow in one direction from being too low that always the red light.

control_signal_ns = pid_ns.compute(current_vehicle_count_ns, step_length, -5, 5)
current_ns_duration=max(min_phase_duration,min(max_phase_duration,current_ns_duration + control_signal_ns))
traci.trafficlight.setPhaseDuration(„J1“, current_ns_duration)

PID controller is used to calculated the additional green length and overrides existing green time for real-time control. The simulation results are plotted in python, Fig.3 shows the vehicle count (which can also be expressed as a queue length) and the total waiting time when using the designed adaptive traffic control system. Which is an important measure of current traffic congestion [5]. It can be seen that the north-south traffic flow has stabilized between 13 and 17 vehicles, showing volatility but is relatively stable. While the east-west traffic flow is overall less, staying between 2 and 5 vehicles. This indicates

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that the system prioritizes the north-south direction in the case of high demand for north-south access. At same time the east-west direction open briefly. In this study, Pre-set north-south and east-west traffic flow in sumo are 9852 and 7007 respectively, which proves that the designed system perfectly change the signal duration according to the real time traffic flow. The total waiting time for cars fluctuates over time, generally between 20s and 80s. And it needs to be aware that at some points the waiting time rises rapidly to 80 seconds, which indicates a sudden change in traffic flow, such as an increase in north-south traffic, resulting in an upsurge in waiting time for east-west vehicles. Compared to the fixed time traffic system in Fig.4, the adaptive traffic signal control system designed in this study reduces the total waiting time by about 84%. Which is demonstrated that the adaptive traffic control system based on PID controller plays a significant role in reducing traffic congestion, conserving energy use and shortening people's travel time.

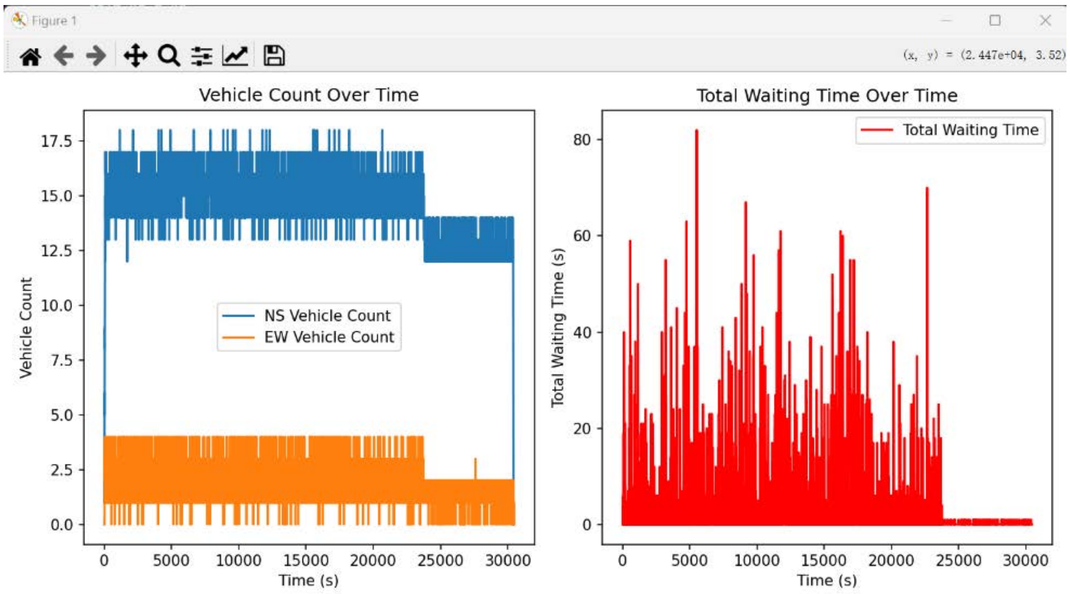

Fig. 3 Simulation results of adaptive traffic signal control system

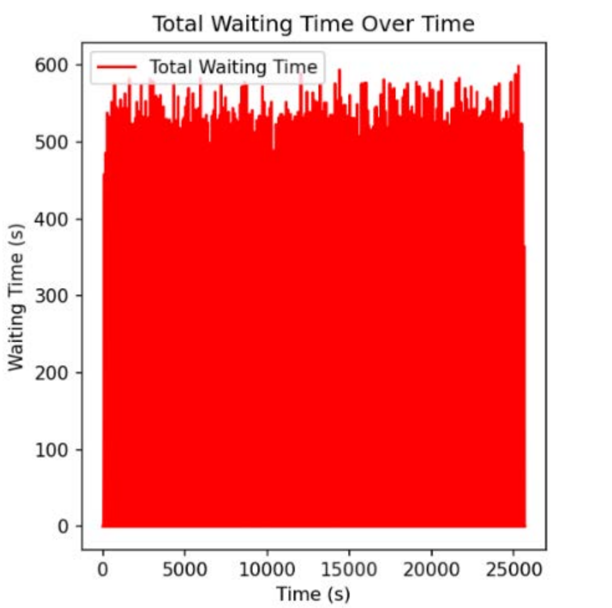

Fig. 4 Total waiting time of fixed time system

4. Discussion

It should be noted that the traffic system modelling in this study is based on assumptions and simulated in python and sumo software but not applied to actual traffic intersections, which has limitations in data collection and modelling. First of all, compared with most of the city using sensors to measure traffic flow, the YOLO based on the monitoring system have been improved in the measurement of speed and accuracy. However, the process of time-consuming, slowing down the speed of the traffic signal changes when the shooting of the traffic road upload to the cloud for analysis. In addition, the traffic system in real world is complex and variable, it may include the influence of different factors such as driver behavior, road conditions (gradient, width) and weather, etc. Simply modelling as a second-order system may be difficult to apply to all situations in real life. Nonetheless, the adaptive PID control system designed in this study has a very great potential in urban traffic management in the future. With the development of smart cities and the application of GPS in vehicles, an iot-based data collection system can be applied to this system to realize the seamless exchange of information between vehicles and traffic signals [10]. Furthermore, this system can also interact with mechanical learning. Xiaoqiang Wang et al. designed Co-DQL, which can eliminate the over-estimation of traditional independent Q-learning while guaranteeing exploration and enable multiple intelligences to cooperate effectively [11]. This can be used to analyze the historical traffic flow, predict the future traffic conditions and fine-tune the coefficients of the PID controllers using AI. Which can be applied to more complex and changing traffic environments in the future.

5. Conclusion

In this study, an adaptive traffic signal control system is designed. Based on the feedback of historical and real-time traffic flow, the PID controller is used to adjust the duration of the signal. By tuning the parameters of PID controller, a well perform step response is obtained. The adjusted PID controller is put into the sumo and python for simulation, plotting the results as “vehicle count over time” and “total waiting time”. The results prove that the set PID controller can accurately adjust the traffic density according to the real-time traffic flow at the intersection. The traffic control system designed in this study plays a significant role in alleviating traffic congestion, minimizing the fuel consumption and shortening people’s travel time. It proposes new modeling ideas for traffic signal control, provides a holistic framework for construction, and helps city managers to make better use of existing infrastructure without costly expansions. With the spread of smart city programs in the future, this system will play a key role in creating a connected urban environment. It can be integrated with self-driving cars, public transportation networks and IoT infrastructure to improve the overall efficiency of urban transportation systems. Making cities more livable and sustainable.

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