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Variable Speed Limit Plate Signs Based on Depth Recognition Control

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Abstract: Predictive control (PC) is an advanced control algorithm, which is widely used in industrial process control. Among them, model-based predictive control (MPC) is an important branch of predictive control. Its basic principle is to use the system model to predict future behavior and determine the current control action by optimizing the objective function. Based on the algorithm combined with three different sections using deep learning technology to identify vehicles and output the optimal speed limit, to achieve the effect of traffic flow optimization.

Keywords: Traffic safety; Variable speed limit; MPC algorithm

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1. Research background

As a core part of the transportation infrastructure, the highway network has a perfect facility system and an efficient, fast, and convenient transportation service capacity. In daily travel, the highway system plays an important role and becomes a key indicator to assess the level of economic development. According to the latest data, as of July 2022, China's total highway mileage was about 461,000 km, and by the end of June 2023, the total number of vehicles had increased to about 426 million vehicles. Through the comparative analysis of historical data, it can be seen that the development of highways in China shows a steady growth trend. However, compared with the growing traffic demand, the speed of highway construction and expansion is relatively backward. This lag leads to the increasing contradiction between traffic demand and road supply, which then becomes the root cause of traffic congestion.

The traffic congestion phenomenon has obvious temporal and spatial characteristics, especially in peak hours and specific road sections. The study shows that when the traffic demand of the main highway exceeds the designed capacity, the bottleneck section will appear and the capacity will decrease, leading to vehicles queuing in the upstream section. As traffic demand continues to grow, congestion on bottleneck sections may spread upstream, further exacerbating traffic congestion. This not only reduces the capacity and service level of roads but also may cause serious problems such as traffic accidents, environmental pollution, and waste of resources.

To solve the problem of traffic congestion, the traditional solution strategies mainly include increasing the construction of traffic lines and related facilities. However, these measures often require significant funding input and high late-stage maintenance costs. In contrast, the global optimization regulation strategy is more advantageous. This strategy does not require a large amount of capital investment, and the later maintenance cost is low, and can fundamentally solve the problem of traffic congestion. Therefore, it is particularly important to find an effective regulation method to maximize the use of highway line resources, reduce the loss, and ensure smooth traffic.

In the field of global optimization control, advanced methods such as the model prediction control (MPC) method and urban traffic signal timing optimization have been widely used. The main advantage of the MPC approach is its ability to adapt to changing traffic flows and consider future traffic conditions, thus providing a more flexible and precise basis for traffic management decisions.

Based on the above analysis, this paper proposes a variable control plate optimization design scheme based on real-time road condition change. The scheme aims to realize the optimal regulation of highway traffic flow by changing the organization of traffic flow in specific sections and peak hours, to improve travel efficiency and smoothness. This research can not only help to alleviate the traffic congestion problem but also provide the scientific basis and technical support for future highway traffic management.

2. Local and international research

Hoogen *et al.* demonstrated the effectiveness of variable speed limit control in reducing speed dispersion and reducing the frequency of traffic waves [1]. Zackor *et al.*, through the comparative analysis of the German expressway, indicated that the variable speed limit control can improve the road capacity by about 5% [2]. Ulfarsson *et al.*, based on U.S. highway data, found that variable speed limit control had significant improvement when speed dispersion was high [3].

Bertini *et al.* compared the data before and after implementing variable speed limit control on an Australian expressway, which confirmed the positive role of this control strategy in reducing travel time [4]. Harbord *et al.* evaluated the implementation effect of variable speed limit control on U.K. highways and found that it not only improved the road capacity but also enhanced the comfort of passengers [5]. A study by Kwon *et al.* on highway construction areas in the United States showed that variable speed limit control reduced speed dispersion by 25% during peak traffic demand hours [6]. Papageoriou *et al.* made an in-depth analysis of the data of variable speed limit control on a European expressway and found that this method realized the stability of traffic flow and improved traffic efficiency by increasing the critical density of road sections [6]. Jonkers *et al.* test on the Dutch highway showed that the application of variable speed limit control can effectively reduce the occurrence of traffic waves [7].

Rivey found that the variable speed limit control implemented on French highways significantly reduced the incidence of traffic accidents [8]. Hoogendoorn *et al.* analyzed the traffic conditions after the implementation of variable speed limit control on Dutch expressways and found that the control measures improved the efficiency of traffic circulation in the control section by about 4% [9,10]. In terms of model research, Hegyi *et al.* improved the expected speed calculation equation of the METANET model and optimized the operation efficiency of traffic flow by adjusting the speed limit value in the upstream speed limit area of the bottleneck section [11,12].

In China, the variable speed limit control technology was first applied to real roads in 1990. Based on the coil data, the speed limit value of 60 km/h, 80 km/h, and 100 km/h is displayed through seven variable speed limit sign boards, corresponding to the traffic state of congestion, and free flow respectively. In recent years, the practical application of variable speed limit control has been conducted on some expressways in China. In 2010, a variable speed limit control system was installed in the 10 km section of Hang Expressway. By analyzing the data collected within half a year, it was found that the variable speed limit control could significantly reduce the dispersion degree of the speed [13,14].

3. Design principle

3.1. Design ideas

The idea is to explore the research background and importance of variable rate-limiting methods and to evaluate the strengths and disadvantages of existing research models. Based on the existing literature, we construct a predictive control model and plan the technical paths and methods of the study. The operation characteristics of expressways are deeply analyzed, especially the traffic flow characteristics during peak hours and special sections. The reduced traffic operating capacity and the variable speed limit control are explained and discussed in detail to assess its potential impact on traffic flow. Combined with the predictive control model (MPC) algorithm and constraints, a predictive control model is proposed to provide theoretical support for the subsequent experiments to achieve the goals of this study. Define a cost function: The cost function is the sum of the squares of the differences between the speed limit and the target speed. Specifically, the goal is to minimize the square sum of vehicle density and speed differences, aiming to optimize traffic flow control and ensure that the vehicle travels under specified speed limits and as close to the target speed as possible to improve the fluency and efficiency of traffic flow. By minimizing the objective function, the optimal control strategy can be determined to optimize the traffic flow. The model parameters were adjusted, and the optimal rate-limit value was determined.

3.2. Study methods

3.2.1. Methods to be adopted

(1) Literature: Through consulting relevant papers, books, pictures, and other materials, understand the current development of deep learning identification technology and OpenCV visual database processing and analysis information, and learn the advanced technology used in related research projects.

(2) Investigation and analysis: To investigate the application status of the existing variable speed limit plates locally and internationally, and to analyze their advantages and disadvantages.

(3) Experimental method: Using the existing conditions, make a prediction model based on deep learning recognition technology, carry out feasibility verification, eliminate other interference factors, and further improve the determined overall research scheme.

(4) Expert consultation: Consult and communicate with professional teachers and professors about the technical problems arising in the research and development process, to gain more experience and inspiration, and speed up the research and development process of group projects.

(5) Summary method: Summarize the problems encountered in MPC and the development and innovation of the prediction and control system through text, photos, data, and other forms, and make the corresponding feasibility proof, to get a complete set of variable speed limit system based on deep learning recognition technology.

3.2.2. Technical route

Firstly, through an extensive review of relevant literature, this research focuses on the application of deep learning recognition technology and OpenCV visual library in information processing and analysis. This helps the research team to quickly develop a research plan that is both reasonable and feasible. Secondly, a variable rate-limiting control system is designed based on deep learning and OpenCV image processing technology. The functions intended to be realized by the system include the identification of the vehicle position and the measurement of the movement speed. Thirdly, this study also established the model and preliminarily completed the design of the overall experimental structure. Finally, the experiment is conducted through the simulation scene to identify the shortcomings of the system in the current stage, and the system is further optimized and improved according to the experimental data, to develop a relatively mature variable rate-limiting control system driven by deep learning.

4. Innovative features

4.1. Vehicle identification and positioning based on deep learning

Design and train deep learning models suitable for vehicle recognition, such as convolutional neural networks (CNN) or pre-trained models (such as ResNet, YOLO, etc.), which are trained through a large-scale vehicle image data set to improve the accuracy and robustness of vehicle recognition.

4.2. Traffic flow analysis and variable speed limit strategy

Accurately judge the number and density of vehicles in each lane, and realize the real-time monitoring and analysis of the traffic flow through the analysis of the traffic flow situation and road conditions. According to the results of the traffic flow analysis and combined with the actual situation of the road, the variable speed limit strategy is designed and implemented, and the goal of traffic fluency and road safety is achieved by adjusting the driving speed of the vehicle.

4.3. Make the models and perform the experiments

A traffic signal light model based on depth identification technology is made to simulate the operation of vehicles under variable speed limits and test and verify the feasibility of the scheme.

5. Application prospects

The technology uses a high-resolution camera, which can accurately capture road images, providing a rich data basis for subsequent traffic monitoring. At the same time, the technology also combines deep learning models, such as convolutional neural networks (CNN), the advanced algorithms that can efficiently process and analyze images to accurately identify vehicles on the road and monitor traffic flow in real time.

To meet the processing needs of large amounts of data, the technology also integrates advanced data processing units, which have strong computing power and can achieve fast data processing and decision-making ability, ensuring that the system can make accurate judgments of traffic conditions in a short time.

Additionally, the technology is equipped with variable information signs (VMS), which can display speed limits in real-time and provide timely road condition information to the driver. Through the wireless communication module, the technology can communicate with the central traffic management system in real-time, and realize information sharing and collaborative processing [15].

The technology has many advantages. Firstly, it is highly flexible and can dynamically adjust the speed limit value according to real-time traffic conditions, weather conditions, or special events to ensure road safety and smooth flow. Secondly, the technology helps to improve road safety and reduce the occurrence of traffic accidents. Thirdly, it can also optimize the traffic flow, reduce the congestion phenomenon, and improve the efficiency of road use [16]. Fourthly, the technology can also help to reduce vehicle emissions, reduce environmental pollution, and achieve green travel. Finally, the system has a high degree of automation, low maintenance cost, and convenient for daily management and maintenance.

6. Conclusion

While the initial investment in the technology may be high, the long-term benefit is significant. By improving traffic efficiency and safety, and reducing the costs caused by accidents and congestion, the technology can bring considerable economic benefits to enterprises and society. In addition, the government's support policies for traffic safety and environmental protection may also provide additional subsidies or incentives for the promotion of the technology to further promote the adoption and application of the technology.

Disclosure statement

The authors declare no conflict of interest.

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