Journal of Electronic Research and Application, 2024, Volume 8, Issue 2
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

# Predictive Control Model Based on the MPC Algorithm on Three Different Road Sections

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**Abstract:** Predictive control is an advanced control algorithm, which is widely used in industrial process control. Among them, model 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. This paper discusses the application of MPC in the prediction and control of the speed of vehicles to optimize traffic flow. It is a valuable reference for alleviating traffic congestion and improving travel efficiency and smoothness and provides scientific basis and technical support for future highway traffic management.

**Keywords:** MPC algorithm; Variable speed limit control; Highway

**Online publication:** March 30, 2024

## 1. Introduction

Predictive control is a control strategy used in many fields, which involves predicting future system behaviors using the system dynamic model and generating the optimal control input to realize the stability and performance requirements of the system. This paper employs the Model Predictive Control (MPC) algorithm for optimizing traffic flow control. The aim is to enable vehicles to adhere to speed limits, maintain proximity to the target speed, and enhance traffic fluidity.

## 2. Research background and its significance

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. 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 kilometers, 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.

Traffic congestion has obvious temporal and spatial characteristics, especially in peak hours and specific road sections. Studies show 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 the bottleneck sections may spread upstream, further exacerbating traffic congestion. This not only reduces the traffic capacity and service level of the highway but also may cause serious problems such as traffic accidents, environmental pollution, and waste of resources.

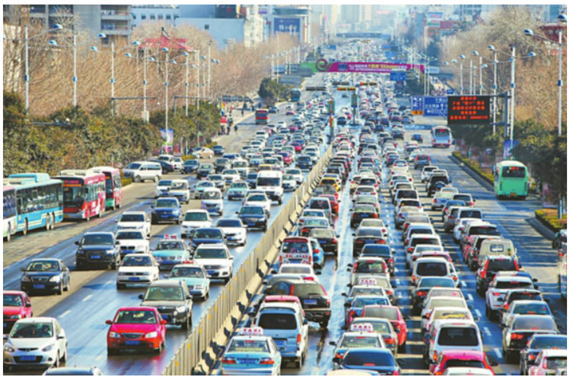

**Figure 1.** Urban congestion real scene map

The traditional solutions for traffic congestion mainly include increasing traffic lines and related facilities. However, these measures often require significant funding and high late-stage maintenance costs. In contrast, the global optimization regulation strategy appears to be more ideal as it does not require a large amount of investment and maintenance costs, and it fundamentally solves 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 loss, and ensure smooth traffic.

In the field of global optimization control, advanced methods such as the MPC method and urban traffic signal timing optimization have been widely used. The MPC method introduces the model prediction control theory into the urban road network traffic management and deals with the oversaturated traffic conditions by adjusting the traffic signal light timing in real time. 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 changes. 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 traffic congestion but also provide scientific basis and technical support for future highway traffic management.

## 3. Overview of relevant domestic and foreign studies

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.*indicated that the variable speed limit control can improve the road capacity by about 5% through a comparative analysis of the German expressway [2]. Ulfarsson *et al.* found that variable speed limit control significantly improved when speed dispersion was high based on

US highway data [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 UK 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.* [6] on highway construction areas in the United States showed that variable speed limit control reduced speed dispersion by 25% during peak traffic demand hours. Papageoriou *et al.* conducted 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. 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 [7,8].

Rivery *et al.* found that the variable speed limit control implemented on French highways significantly reduced the incidence of traffic accidents [8,9]. 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]. Saha *et al.* found a significant reduction in the number of traffic accidents after the implementation of variable speed limit control [10,11]. In terms of model research, Hegyi *et al.* improved the expected speed calculation equation of the Metanet model. They 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]. Allaby *et al.* proposed a variable rate-limiting control strategy based on the real-time traffic state, verified its effectiveness in the Paramics simulation model, and determined the threshold of the relevant parameters [12,13]. Hegyi *et al.* developed a variable speed limit control model capable of detecting and controlling traffic waves and verified its role in alleviating traffic waves through field testing [13,14].

Hellinga *et al.* deeply explored the influence mechanism of driver compliance on the control effect and verified the positive correlation between the two through simulation using Paramics Discovery [14,15]. Papageorgiou *et al.* controlled the traffic flow by adjusting the speed limit upstream of the bottleneck section, therefore avoiding the decrease of traffic capacity at the bottleneck and improving the overall traffic efficiency [15,16]. Carlson *et al.* proposed a feedback control algorithm based on the Metanet model and confirmed that the control measure can improve the traffic flow rate of the bottleneck section and reduce the travel time by 30% [16,17].

In China, the variable speed limit control technology was first applied to real roads in 1990. Based on the coil data, the speed limits of 60 km/h, 80 km/h, and 100 km/h are displayed through seven sign boards, corresponding to the traffic state of congestion, following, 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 the expressway. By analyzing the data collected within half a year, it was found that the variable speed limit control could significantly reduce the speed dispersion [17,18]. In 2013, the variable speed limit control system was adopted to conduct traffic control in special bad weather. The practical application proved the positive role of the variable speed limit control system in improving safety and reducing accident rates [18]. Moreover, Papageorgiou built on Payne and proposed the second-order METANET model, which provided an effective tool for traffic flow prediction.

## 4. Introduction of the MPC algorithm

Predictive control is an advanced control algorithm, which is widely used in industrial process control. Among them, model-based predictive control is an important branch of predictive control. Its basic principle is to use the system model to predict the future behavior and determine the current control action by optimizing the objective function.

## 4.1. MPC predictive control method

The predictive control method based on MPC algorithm mainly includes the following steps:

### 4.1.1. Defining the objective function

The core of MPC is defining an objective function about the system state and control variables. This objective function is optimized at each step to minimize a specific performance metric, such as system output, energy expenditure, etc.

### 4.1.2. Establishing the system dynamic model

To predict future system behavior and optimize control actions, a model that describes the dynamic behavior of the system is needed. The model is usually a linear or non-linear model, which is built based on the historical data of the system and the known dynamic characteristics.

### 4.1.3. Handling the constraints

In real systems, the control input and state variables usually have some constraints, such as maximum / minimum, rate limit, etc. The MPC algorithm considers these constraints during the optimization process to ensure that the control action is within the feasible range.

### 4.1.4. Rolling optimization

MPC uses online optimization to optimize future control actions at every moment, then performs the optimal control actions and update the model to reflect the new state. This process is repeated, creating the so-called "rolling optimization".

## 4.2. Discussion of the advantages and disadvantages of the MPC algorithm

The predictive control method based on the MPC algorithm presents several advantages.

(1) Flexibility: MPC can handle complex constraints and objective functions, making it suitable for a variety of different systems.

(2) Real-time adjustment: Because MPC is an online optimization algorithm, it can adjust the control action in real time.

(3) Prediction: MPC can predict future system behavior and perform control and adjustments in advance.

However, the predictive control method based on the MPC algorithm also has some limitations.

(1) Model requirements: In order to run the MPC algorithm, an accurate system model is needed. If the model is inaccurate, the optimization results may be unsatisfactory.

(2) Computational complexity: MPC is a complex optimization problem that requires online optimization at every moment. For large-scale systems, the computational requirements may be high.

(3) Constraint management: Handling constraints (especially hard constraints) can be complex, and algorithms need to be carefully designed to ensure the stability of the system.

In short, predictive control methods find applications and offer numerous advantages in industrial process control, but they also pose certain challenges. Through continuous improvement of algorithms and models, predictive control methods can play a greater role in scientific research and practical applications.

## 5. Objectives and procedure

### 5.1. Objectives

This paper aims to develop an MPC algorithm-based model to predict and control the speed of vehicles in traffic flow to optimize the flow and stability of traffic flow. The optimization objective is to minimize the overall cost in the traffic flow system, where the cost includes the square sum of the differences between vehicle density and speed. This cost function can be used to measure the degree of traffic flow instability and congestion.

### 5.2. Procedure

(1) The background and research significance of variable rate-limiting methods were analyzed, and the advantages and disadvantages of relevant research models were outlined. Based on the related studies, the predictive control model was proposed, and then the research technique and route were determined.

(2) The characteristics of expressway operations were investigated, and the traffic flow during peak hours and operations of special sections were clarified. The reasons for the decline in operation capacity and the influence of variable speed limit control on traffic flow were deduced.

(3) Based on the MPC algorithm, a predictive control model was proposed to provide a theoretical basis for relevant experiments, so as to better realize the research objectives of this paper.

(4) The cost function was obtained through the sum of the difference between the speed limit and the target speed. (5) Specifically, the goal was to minimize the sum of squares of the difference between vehicle density and speed, and the purpose of this function is to optimize traffic flow control and ensure that the vehicle travels according to the speed limit to improve traffic flow. By minimizing the value of the objective function, we can implement the optimal control strategy, which in turn maximizes the efficiency of traffic flow.

The relevant parameters of the model were debugged, and the optimum speed limit was output.

**Figure 2** shows the flow chart of the procedure involved.

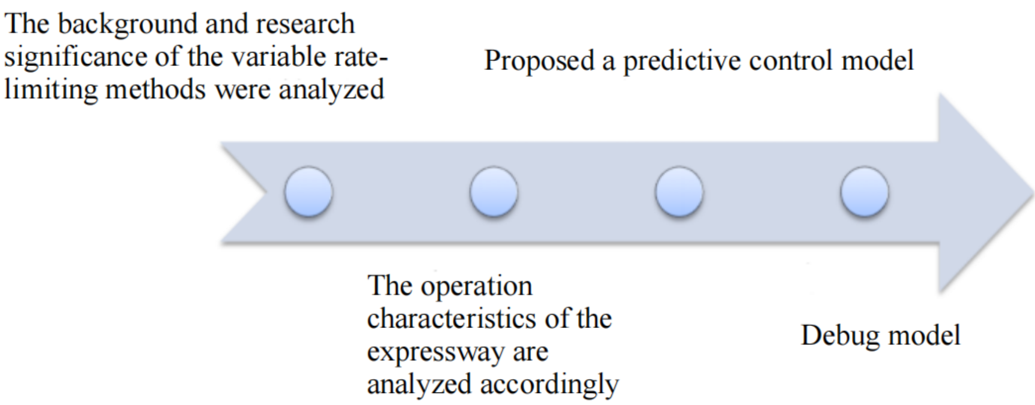


**Figure 2.** Task flow chart

# 6. Model introduction

## 6.1. Parameter introduction

| Parameter | Meaning |
|---|---|
| alpha | Speed limit model parameters |
| vf | Free flow speed |
| kc | Congestion density |
| tau | Acceleration time length |
| lanelength | Lane length |
| num | Number of predicted time steps |
| meta | Vehicle arrival rates on the on-ramp |
| time_interval | Number of queuing vehicles on the on-ramp |
| ramp queue | Time interval |
| ramp arrive | Number of time steps predicted by the model |
| Qr | Maximum vehicle density |
| kj | Vehicle acceleration parameters |
| κ | Inlet-ramp flow allocation parameters |
| r | Inlet-ramp flow impact parameters |
| δ | Proportional parameters of the vehicle speed and flow rate |
| β | Control the ratio of vehicle speed and flow rate |

## 6.2. Code introduction

We built three different control models for different road sections

### 6.2.1. Speed limit road section

We used a rate-limiting model to calculate the post-control speed. The speed-limiting model was nonlinear, and we adjusted the parameter f to control the extent of speed limit calculation. The velocity-flow relationship function, denoted as F {1, vc} {1, sp} (1, l + 1), was derived from vehicle density and speed, representing the maximum speed achievable under different densities. Furthermore, the free-flow velocity vf was defined as the maximum speed a vehicle could reach in uncongested conditions.

The vehicle density k (j-1, lmeta + i) represents the density of vehicles at the previous moment, while the congestion density kc is defined as the vehicle density at which the road becomes congested. By considering the difference between flow and imported/exported vehicles, we compute the new vehicle density (k_new). The vehicle speed v at the previous moment (j-1, lmeta + i) denotes the vehicle's speed, and the acceleration time constant tau is utilized to regulate the response time for vehicle acceleration and deceleration.

We used the time interval (time_interval) to calculate the rate of change of vehicle speed and obtained the new vehicle speed v_new by calculating the speed-limiting model, vehicle density, and rate of speed. β was used to control the ratio of vehicle speed and flow rate.

### 6.2.2. Fast section

Firstly, we computed the post-control speed using the rate-limiting model. Then, we determined the variance between the flow and the imported/exported vehicles. Subsequently, we utilized the rate of change and acceleration time constant to ascertain the new vehicle speed. Additionally, we took into account other factors such as managing vehicle acceleration and the ratio of vehicle speed to flow. This code simulates traffic flow in the on-ramp section and dynamically calculates the variable speed limit based on real-time vehicle density and speed.

### 6.2.3. Ramp section

First, we calculated the controlled velocity (V_after_ctrl) according to the rate-limiting model, which takes into account the effect of vehicle density on speed. Then, we calculated the inflow (inflow) of the on-ramp, based on the location and the number of lanes. For the first lane, we also calculated the variation of the ramp queues (ramp_ queue). Next, we calculated the new vehicle density (k_new) based on the difference between flow rate and import and export vehicles. Then, we calculated the new rate of change (v_new) using the acceleration time constant (tau). Meanwhile, we considered other factors, such as the parameter meta controlling the vehicle acceleration, the flow control parameter (δ), the proportional parameter of vehicle speed and flow (β), etc. Next, we calculated the new vehicle flow rate (q_new) based on the new vehicle density and speed. We then updated the total density (ρ), total vehicle density ($\rho_T$), and total flow rate ($\rho_D$). Lastly, the new vehicle density, speed, flow, and control signals were set as the corresponding variables.

In the last line of code, we calculated the variable speed limit (variable_speed_limit ), which was the minimum of all vehicle speeds in the current lane. This limitation was used to determine the maximum speed that the current lane could implement.

## 7. Conclusion

This paper introduces a predictive control model based on the MPC algorithm to optimize highway traffic flow. The model combines three sections to propose variable speed limit control methods, which can predict and control the traffic flow to improve highway traffic efficiency and alleviate traffic congestion. The main goal of the model is to optimize the control of traffic flow so that the vehicle travels below the speed limit to improve traffic fluency. The optimal control strategy is obtained by minimizing the sum of the squares between the speed limit and the target speed. The model also takes into account the constraints of the variable rate-limiting control method. Finally, the model is implemented by Matlab programming and the relevant parameter debugging and the output of the best rate-limiting values.

## Disclosure statement

The authors declare no conflict of interest.

## References


[1] Hoogen E, Smulders S, 1994, Proceedings of the Seventh International Conference on Road Traffic Monitoring and Control, April 26–28, 1994: Control by Variable Speed Signs: Results of the Dutch Experiment. London, 145–149.

[2] Zackor H, 1979, Self-Sufficient Control of Speed on Freeways. Proceedings of the International Symposium on Traffic Control, 2: 226–249.

[3] Ulfarsson GF, Shankar VN, Vu P, 2005, The Effect of Variable Message and Speed Limit Signs on Mean Speeds and Speed Deviations. Int. J. of Vehicle Information and Communication Systems, 1(1/2): 69–87.

[4] Bertini L, Boice S, Klaus B, 2005, Proceedings of the 8th International IEEE Conference on Intelligent Transportation

Systems, September 13–16, 2005: Using ITS Data Fusion to Examine Traffic Dynamics on a Freeway with Variable Speed Limits. Vienna, 1006–1011.
[5] Safran C, Reti S, Marin HF, 2010, MEDINFO 2010: Proceedings of the 13th World Congress on Medical Informatics, Volume 160 Studies in Health Technology and Informatics - 2 Volume Set, IOS Press, Amsterdam.
[6] Papageorgiou M, Kosmatopoulos E, Papamichail I, 2008, Effects of Variable Speed Limits on Motorway Traffic Flow. Transp Res Rec, 2047(1): 37–48.
[7] Jonkers E, Wilmink IR, Stoelhorst H, et al., 2011, Proceedings of the 2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC), October 5–7, 2011: Results of Field Trials with Dynamic Speed Limits in the Netherlands: Improving Throughput and Safety on the A12 Freeway. Washington, DC, 2168–2173.
[8] Rivey F, 2010, Easy-Way Annual Forum, November 17, 2010: Evaluation of the Dynamic Speed Limit System on the A13 Motorway in France [Conference Presentation].
[9] Kianfar J, Edara P, Sun C, 2013, Proceedings of Transportation Research Board 92nd Annual Meeting, January 13–17, 2013: Operational Analysis of a Freeway Variable Speed Limit System: Case Study of Deployment in Missouri. TRB Committee AHB15 Intelligent Transportation Systems, Washington DC.
[10] Saha P, Young R, 2007, Transportation Research Board 93rd Annual Meeting, January 12–14, 2014: Weather-Based Safety Analysis for the Effectiveness of Rural VSL Corridors [C] Transportation Research Board. Washington DC
[11] Hegyi A, De Schutter B, Hellendoorn J, 2003, Optimal Coordination of Variable Speed Limits to Suppress Shock Waves. Proceedings of the 42nd IEEE Conference on Decision and Control, 2768–2773.
[12] Allaby P, Hellinga B, Bullock M, 2003, Proceedings of the 2006 IEEE Intelligent Transportation Systems Conference, September 17–20, 2006: Variable Speed Limits: Safety and Operational Impact of a Candidate Control Strategy for an Urban Freeway. Toronto, 897–902.
[13] Hegyi A, Hoogendoorn SP, Schreuder M, et al., 2008, Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems, October 12–15, 2008: SPECIALIST: A Dynamic Speed Limit Control Algorithm Based on Shock Wave Theory. International IEEE Conference on Intelligent Transportation Systems. Beijing, 827–832.
[14] Hellinga B, Mandelzys M, 2011, Impact of Driver Compliance on the Safety and Operational Impacts of Freeway Variable Speed Limit Systems. Journal of Transportation Engineering, 137(4): 260–268.
[15] Carlson RC, Papamichail I, Papageorgiou M, et al., 2010, Optimal Motorway Traffic Flow Control Involving Variable Speed Limits and Ramp Metering. Transportation Science, 44(2): 238–253.
[16] Carlson RC, Papamichail I, Papageorgiou M, 2011, Local Feedback-Based Mainstream Traffic Flow Control on Motorways Using Variable Speed Limits. IEEE Trans. Intelligent Transportation Systems, 12(4): 1261–1276.
[17] Duan H, Liu P, Wan J, et al., 2012, Proceedings of the 12th COTA International Conference of Transportation Professionals, August 3–6, 2012: Evaluating the Impacts of Variable Speed Limits on Freeway Traffic Operations and Safety: A Case Study in Hangzhou, China. American Society of Civil Engineers, Beijing, 2615–2626.
[18] Li Z, 2014, Variable Speed Limit Control Technology for Fast Roads, dissertation, Southeast University, Nanjing.