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MULTI-OBJECTIVE OPTIMISATION OF A VARIABLE SPEED LIMIT CONTROL STRATEGY IN A TUNNEL MAINTENANCE WORK ZONE OF THE MOUNTAIN HIGHWAY

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Abstract. Variable Speed Limit (VSL) control is essential for managing highway tunnel maintenance work, as it adjusts speed limits based on road conditions to regulate traffic flow. Developing a VSL control strategy that balances traffic efficiency and safety during maintenance can be challenging. This paper addresses this issue by proposing a VSL control strategy based on Model Predictive Control (MPC) that considers the spatial characteristics of traffic flow in a tunnel maintenance work zone. The strategy aims to minimise total travel time, reduce speed variance, and maximise traffic flow through a multi-objective optimisation approach using a Non-dominated Sorting Genetic Algorithm II (NSGA-II). With the Qinling Tiantai Mountain Tunnel selected as the experimental object, a simulation

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section is constructed based on the SUMO model with the measured data, and a comparative experiment of different speed limit control cycles in the maintenance work zone is designed. The results show that the method of this paper can effectively reduce the total travel time under the influence of maintenance operations by more than 17.5%, reduce the standard deviation of speed by about 22.1%, and enhance the traffic volume by about 7.8%, which can effectively improve the efficiency of road access and safety level.

Keywords: MPC control strategy, multi-objective optimization, NSGA-II, SUMO simulation, tunnel maintenance work zone, VSL control.

Introduction

With the increasing number of highways, the number of highway tunnels is also on the rise. This improves travel efficiency but also increases the likelihood of congestion and traffic accidents (Caliendo et al., 2022). The complexity and dynamic characteristics of tunnel environments pose greater challenges to traffic management in maintenance work zones. Factors such as insufficient lighting, variations in pavement conditions, and limited sight distance further increase accident risks and management difficulties in these areas. Conventional measures, such as static signs and manual control, are often insufficient to address the rapidly changing traffic conditions in such environments. Therefore, a more flexible and effective management strategy is needed.

VSL control is one of the primary strategies in active traffic management. VSL control not only mitigates congestion by coordinating road capacity and traffic demand (Du & Razavi, 2020; Frejo et al., 2019), but it also plays a critical role in enhancing traffic stability and improving overall efficiency. Based on the data of traffic accidents in highway maintenance work zones, an analysis of the accident situation was conducted. It was found that the accident rate obviously showed an increasing trend, and the driving risk in the maintenance work zone was high (Wang et al., 2022; Wang & Lee, 2021). Identifying the accident risk level in the tunnel maintenance work zone and dividing the speed limit interval and value are important steps. These measures can reduce the standard deviation of speed between vehicles in adjacent road sections within the interval. This, in turn, minimises the risk difference and reduces the possibility of accidents (Jin et al., 2024). A VSL optimisation algorithm model is established based on the improvement of road capacity. The results indicate that VSL control substantially improves road traffic efficiency (Wu et al., 2020).

Multi-dimensional factors should be comprehensively considered when a speed limit is applied in the tunnel maintenance work zone. Different factors have different degrees of influence on the driving speed (Zuraulis & Surblys, 2021). By analysing the running speed, it is possible to obtain the speed distribution law (Leonavičienė et al., 2020; Mazrekaj et al., 2022), the characteristics of vehicle speeding (Gaveniene et al., 2023; Kreicbergs et al., 2021; Sorum & Sorum, 2025), and the layout scheme of the maintenance work zone (Li et al., 2024). By analysing the traffic flow in the maintenance work zone, it was concluded that the risk level of driving within different zones is different (Yang et al., 2017). Traffic conflicts between vehicles within the upstream merging zone were found to be mainly caused by the mandatory merging of vehicles, which was the main reason for the generation of traffic conflicts within the upstream merging zone (Huang et al., 2023). VSL strategies control the capacity drop and increase the vehicle dissipation rate by controlling the upstream traffic operation and eliminating queuing at bottleneck sections (Cho & Laval, 2020; Du & Razavi, 2019; Kim et al., 2024).

Existing studies mainly focus on either tunnel segments or maintenance work zones, overlooking their combined effects on traffic flow. Moreover, most VSL optimisation models are single-objective and cannot simultaneously balance safety and efficiency. To this end, for a maintenance work zone in a mountainous highway tunnel, an MPC-based VSL optimistion algorithm is proposed. The algorithm constrains the maximum speed, the smoothness of the speed limit over time, and acceleration. It takes the upstream section speed, traffic volume, and large vehicle rate as inputs. The goal is to improve traffic efficiency and safety. Unlike conventional VSL studies that mainly focus on open-road scenarios, the proposed approach explicitly accounts for tunnel-specific constraints and dynamic disturbances and employs the NSGA-II for solutions, and its effectiveness is verified by SUMO simulation under the measured data of the Qinling Tiantai Mountain Tunnel.

1. Literature review

1.1. VSL research methodology and control modelling

It is found that the VSL control system can flatten the slope of the traffic occupancy curve and move the point of the highest value of the critical occupancy backward after the vehicle exceeds the critical density, which confirms the theoretical basis of the VSL control system (Wang et al., 2021). At present, the theory of VSL control is widely used in the research of the maintenance work zone, and more mature research methods and control models have been formed, such as the METANET model, the Cell Transmission Model (CTM), Machine Learning (ML), and the MPC model. Referring to the MPC theory and combining speed limit controls with the ramp control method, a closed-loop and real-time feedback integrated control method is proposed (Han et al., 2017; Muralidharan & Horowitz, 2015). The VSL macroscopic model is used, which takes into account the capacity and critical density of the roadway sections affected by speed limits (Fauchet et al., 2024; Zhang et al., 2024). A VSL system suitable for freeway bottleneck areas was designed to mitigate traffic congestion by implementing well-defined VSL strategies. However, validation was conducted separately for tunnel entrance and merging area bottlenecks (Niu et al., 2022).

1.2. VSL optimisation objective

Applying VSL control effectively eliminates some traffic fluctuations, leading to lower accident rates (Zhai et al., 2023). According to the different optimisation objectives, the objective function and constraints in the VSL control model are changed. The VSL control can be used to reduce the effects of shock waves (Han et al., 2021); however, it must be optimised to avoid the emergence of new shock waves from changes in speed limit values or negatively affecting traffic flow at other locations (Greguric et al., 2022). Therefore, step-by-step methods for controlling speed limits have been proposed to prevent drivers from encountering adjustments that are greater than the range of safe speed limit changes. Different combinations of speed limit cycles and adjacent time-space speed limit differences in high-speed maintenance work zones are used as VSL control strategies to solve the optimal control strategy with passage efficiency as the optimisation objective (Gao et al., 2024). A simulated kinematic wave propagation model is constructed, and the safety effect is improved significantly under slight congestion and severe congestion scenarios (Abdulghani & Lee, 2022). However, most existing research only considers traffic efficiency or safety as a single goal and rarely considers the balance between the two simultaneously. Based on this aspect, to minimise the accident rate and the speed limit as the constraint, the VSL control optimisation model is developed, and the model is solved using a genetic algorithm (Guo et al., 2022; Zhang et al., 2023). The real-time collision risk assessment model is utilised to quantify the accident risk, and the optimal VSL control strategy is solved to minimise the total collision risk (Chen & Qin, 2019; Hou & Chen, 2020).

In summary, the current domestic research on VSL in the maintenance work zone of tunnel sections on mountainous highways is still in the exploratory stage. Existing research focuses on the speed limit control of the highway maintenance work zone, ignoring the special driving environment of the tunnel section and the double impact of the maintenance work zone setting on the traffic flow. At the same time, the reasonable speed limit value on the road section of the tunnel maintenance work zone will be constantly changed under the influence of many factors, such as the operation status of the traffic flow, and the traditional highway Static Speed Limit (SSL) method cannot reflect the characteristics of the changing road traffic environment. At present, most of the studies take traffic efficiency or driving safety as the optimisation objective, and fewer studies take into account traffic efficiency and safety at the same time. Therefore, it is necessary to construct a multi-objective

VSL optimisation framework that is more in line with the complex constraints of tunnel maintenance work zones.

2. Methodology

2.1. MPC-based active control strategy

MPC is a model-based optimal feedback control method for control systems with predictable operating states and perceptible external perturbations that can consider traffic conditions in a finite time domain (Han et al., 2017). The advantage of MPC-based control of tunnel speed limits is that it can effectively solve nonlinear situations containing complex constraints, while only one controller is needed to manage multiple inputs and multiple outputs of the system, which is more efficient and accurate in dealing with traffic flow in tunnels. Therefore, in the SUMO simulation environment, this article combines the XGBoost traffic state prediction model with the multi-objective control function shown in Figure 1 to construct a nonlinear MPC optimal VSL control strategy model for tunnel maintenance work zones.

First, we obtain the traffic flow parameters upstream of the study section, including average speed, traffic volume, large vehicle rate, and time period; input the relevant information of the traffic flow into the control algorithm; use the XGBoost algorithm for prediction, providing nonlinear input for MPC to update the control parameters; and use the NSGA-II algorithm under the constraints of the maximum value of vehicle speed, the maximum value of acceleration, and the smooth constraints of the speed limit; and finally, we output the optimal VSL sequence. The scheme takes into account the efficiency and safety in the maintenance work zone of mountain highway tunnels.

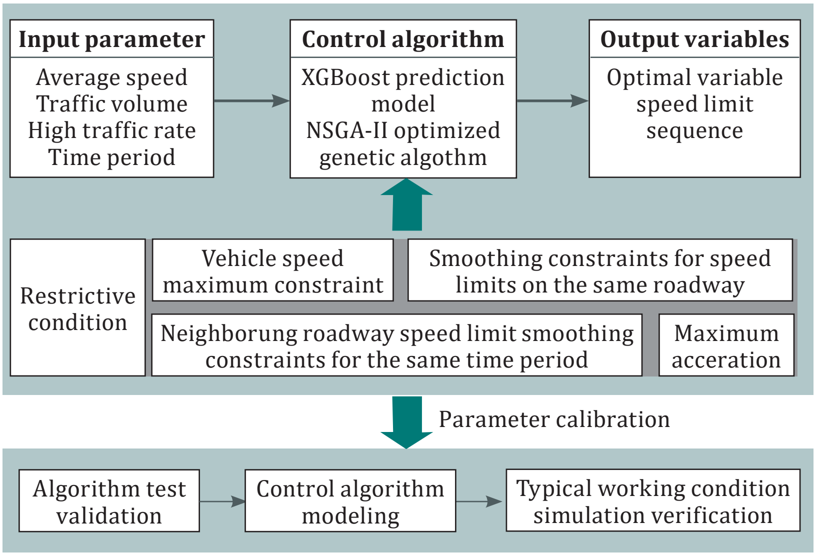

Figure 1. Model of MPC-based VSL control technique

2.2. XGBoost-based traffic flow prediction

In the process of real-time VSL control, to ensure the real-time speed limit control, it is necessary to predict the short-time traffic state of the tunnel in advance (such as the average speed, traffic volume, and the rate of large vehicles) to support the optimal speed limit control scheme selection algorithm. The VSL control effect is directly affected by the prediction accuracy and prediction speed of the short-time traffic prediction model in the tunnel environment. The XGBoost algorithm has the advantages of supporting parallel computing, automatically learning the processing strategy for missing values, and efficiently processing features with a large number of 0 values, etc. It achieves the purpose of controlling the complexity of the model and providing a variety of parameters to regulate its performance by adding a regularization term to the objective function.

Equation (1) represents the Mean Squared Error (MSE) as the loss function of XGBoost and its calculation formula. The objective function combines the loss function and regularization term and controls the model complexity by adding a penalty term for regularization, preventing overfitting, and improving the model's generalization ability. The form is shown in Equation (2).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2, \tag{1}$$

$$\min_f\left[\sum_{i=1}^{n} l\left(y_i,\hat{y}_i\right)+\Omega\left(f\right)\right], \tag{2}$$

where MSE represents a mean square error; N – the number of samples; y_i – the actual value of the sample i; $\hat{y}_i$ – the predicted value of the sample i; $l(y_i, \hat{y}_i)$ – the loss function; $\Omega(f)$ – the regularization term.

The XGBoost algorithm is suitable for large-scale datasets. In this study, the sample dataset is divided into a 70% training set and a 30% testing set. The model is trained using the training data, and the prediction accuracy of the trained model is then evaluated using the testing data. The prediction accuracy is characterised by the Root Mean Square Error (RMSE) and the Mean Absolute Percentage Error (MAPE). In this research, the input samples to the model include independent variable parameters and corresponding dependent variable parameters. The independent variable parameters are the average speed, traffic volume, and heavy vehicle rate within the current speed limit period in the maintenance work zone. The dependent variable parameters are the average speed, traffic volume, and heavy vehicle rate in the next speed limit period in the maintenance work zone.

2.3. Constructing constraints

When there is a significant difference in speed limit between neighbouring road sections, drivers need to accelerate or decelerate frequently to adapt to the new speed limit. By setting the speed difference and acceleration appropriately, vehicles can transition more smoothly and reduce the probability of traffic wave formation. This helps maintain the stability of traffic flow and improves driving safety. Overall, reasonable constraints can produce a smoother and safer traffic environment. When implementing the optimal VSL combination operation for the maintenance work zone in the highway tunnel, the speed limit values must adhere to the following requirements to satisfy driving safety:

The upper limit of the VSL cannot exceed the maximum speed limit value of the roads at all levels specified in the specification, nor can the lower limit be less than the speed limit value of the construction and maintenance work zone specified in the specification.

To enhance the safety and effectiveness of the VSL control strategy, this study introduces a spatiotemporal smoothing constraint mechanism in the speed limit scheme generation process. Specifically, in terms of time dimension, to avoid the risk of rear end collision caused by a sudden drop in downstream speed limit values, the speed limit should gradually decrease from upstream to downstream along the same road section, and the difference in speed limit between adjacent positions should not exceed 20 km/h. In the spatial dimension, to reduce lateral conflicts and forced lane changes caused by large speed differences between adjacent lanes or road sections, the speed limit difference is set to no more than 20 km/h to ensure the smoothness and operability of the speed adjustment process. The above constraint criteria refer to the research by Cheng and Cheng (2020), verifying through empirical and simulation that setting the speed limit value in a gradient of 20 km/h was appropriate in scenarios such as road reconstruction and expansion work zones.

Acceleration changes in the range of –2.5 m/s^2 to 3.5 m/s^2. The acceleration of the vehicle in the entire road section should be within a reasonable range to minimise traffic fluctuations.

Gradient constraints on the speed limit value: generally take an integral multiple of 10 km/h.

$$v_{\min} \le v_j(t+k) \le v_{\max}, \tag{3}$$

$$\left| v_j(t+k+1) - v_j(t+k) \right| \le 20, \tag{4}$$

$$\left| v_{j+1}(t+k) - v_j(t+k) \right| \le 20, \tag{5}$$

$$a_{\min} \le a_i \le a_{\max}, \tag{6}$$

$$\frac{v_j(t+k)}{10} = P\left(P \subset N^*\right), \tag{7}$$

where $v_{\min}$ and $v_{\max}$ are the lower and upper limits of the design speed required by the specification of the control road section, respectively. $v_j(t+k+1)$ is the speed limit value of the j speed limit sign at the moment $(t+k+1)$; $v_j(t+k)$ is the speed limit value of the j speed limit sign at the moment $t+k$; $v_{j+1}(t+k)$ is the speed limit value of the j+1 speed limit sign at the moment $t+k$; $a_{\min}$ and $a_{\max}$ are the maximum permissible deceleration and acceleration, respectively, of the control road section; a_i is the acceleration of the i vehicle; N^* refers to the set of positive integers.

2.4. Constructing an objective function based on the NSGA-II algorithm

Considering that the units of the selected objective function are not uniform, and the meanings of the realities they represent are inconsistent, and it is difficult to be converted into a single-objective optimisation function by weighted average, the NSGA-II algorithm is chosen to solve the multi-objective optimisation problem, including the purpose of improving traffic efficiency and safety. The optimal VSL control scheme is selected. The NSGA-II algorithm is based on the concept of Pareto optimality, which searches for the optimal solution set of the problem by simulating the process of natural selection. The algorithm can determine a set of solution sets that are balanced among multiple objectives rather than a single optimal solution.

Unreasonable speed limit control of highway tunnel maintenance work zone road sections will not only lead to the decline of the main line capacity but also make it easy to cause traffic accidents, affecting road traffic safety. Therefore, in the comprehensive consideration of access efficiency and traffic safety to determine the evaluation index, access efficiency is characterised by the total travel time and total flow in the control cycle, and traffic safety is characterised by the average of the standard deviation of the speed measured by the detector. Combined with the formula, the objective function of the multi-objective optimisation of the VSL control strategy for a highway tunnel maintenance work zone is established.

The objective function consists of three indicators: total travel time, standard deviation of speed, and total flow, to improve the passage efficiency, guarantee the driving safety, and ensure the smoothness of the control of adjacent speed limit plates. Total Travel Time (TTT) is minimised; Speed Standard Deviation (STD) is minimised; Total Flow (TF) is maximised.

$$\min Z = \alpha \times TTT + \beta \times STD - \gamma \times TF, \tag{8}$$

$$1 = \alpha + \beta + \gamma, \tag{9}$$

$$TTT = \sum_{i=1}^{Q_T} t_i, \tag{10}$$

$$STD = \sqrt{\frac{1}{Q_T}\sum_{i=1}^{Q_T}(v_i - \overline{v}_T)^2}, \tag{11}$$

where Q_T is the total number of vehicles in the control cycle; t_i is the travel time of the *i* vehicle in the control cycle; v_i is the speed of the *i* vehicle in the control cycle, and $\overline{v}_T$ is the average speed of all vehicles in the control cycle; α represents the weight of *TTT*; β represents the weight of *STD*, and γ represents the weight of *TF*.

Through the analysis of the causes and processes of traffic fluctuations in the tunnel maintenance work zone and the collation of statistics, a preliminary set of weights for the objective function's indicators was constructed. Given that traffic fluctuations are complex and difficult to quantify due to multiple factors, such as weather, construction, and traffic control, maintenance decisions need to take into account multiple objectives, such as safety and efficiency. Additionally, there are limitations in the basic data. This study adopts the expert scoring method, relying on domain expert knowledge, and uses Equation (12) to organise the objective function of the indicators' weight matrix $F^{(h)}$. After determining the basic data for authorisation, expert opinions are integrated through Equation (13) to reflect the degree of impact of the indicators. A reasonable evaluation and weight allocation of influencing factors can be achieved, providing a scientific basis for optimising maintenance strategies.

$$F^{(h)} = \left[a_i^{(h)}\right]_n, \tag{12}$$

where h is the order of the experts; a_i is the weight assigned to each indicator by h expert.

$$a_{ij} = \frac{1}{e}\sum_{h=1}^{e} a_i^{(h)}$$
$$F' = \left[a_i\right]_n \quad , \tag{13}$$

where e is the number of experts.

3. Case study

3.1. Data collection and preparation

The Qinling Tiantai Mountain Tunnel is 15.56 km long, with a clear width of 14 m, a clear height of 5 m, and a maximum depth of 973 m. It is designed as a separated two-way, six-lane highway over the ridge tunnel, with a design speed of 80 km/h. The study selected the time period of high holiday traffic density to analyse. Surveillance camera video from the specific time period of 11:00 to 12:00 was selected.

This paper focuses on the VSL control for the highway tunnel maintenance work zone, which requires the section's parameters as input for the control model. Therefore, this paper selects the monitoring video in the Qinling Tiantai Mountain Tunnel to obtain traffic information, such as traffic volume, speed, and large vehicle rate. In the study, a 1 h video of the tunnel monitoring during the peak period was collected and processed offline. Since the surveillance video data is dynamic, it is not possible to obtain the traffic operation status directly. Therefore, the Yolo + DeepSort algorithm was used to track the vehicles in motion, and the trajectory data of 2595 small cars and 112 large cars passing through the tunnel was obtained, which was used for further content, such as large vehicle rate extraction and traffic flow statistics.

The vehicle target detection process based on Yolo mainly consists of three parts: dataset production, model training, and model testing. The video data is cut into images and labelled with vehicles in different motion states, using Labelling about 8200 times, and the ratio of the training set to the dataset is 7:3, with a total of 300 rounds of training. The training results are illustrated in Figure 2, where the validation set mAP@0.5 remains stable at 0.90, indicating accurate and reliable detection results under the standard IoU threshold. Additionally, mAP@0.5:0.95 reaches 0.55, demonstrating that the model exhibits good generalization ability across various IoU threshold ranges. At the same time, the precision remained above 0.80, and the recall was about 0.85, indicating that the model achieved a good balance between controlling false positives and false negatives. Overall, the model has stable convergence, high detection accuracy, and strong robustness. The output trajectory data has adequate accuracy and is suitable for further in-depth analysis. Figure 3 shows the effect of using video verification for target detection.

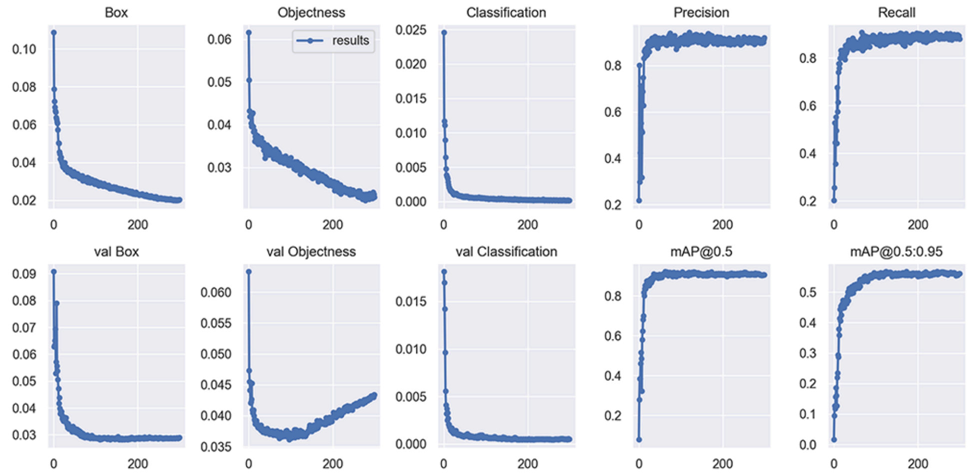

Figure 2. Training effect

Figure 3. Video verification effect

On the basis of target detection, combined with the DeepSort algorithm to detect the frame centre of mass and cascade matching, in the tunnel monitoring video screen, a preset virtual counting line is used. When the vehicle's centre of mass crosses the counting line, you can record a count. To complete the vehicle trajectory detection, predictive tracking, and counting, complete the traffic flow statistics by vehicle type; the counting effect is shown in Figure 4. At the same time, the trajectory data for each vehicle can be output at this stage, including the number of video frames, vehicle number, vehicle category, vehicle coordinates, and so on. By analysing and processing the output vehicle trajectory data, vehicle speed, traffic volume, and other information are finally obtained.

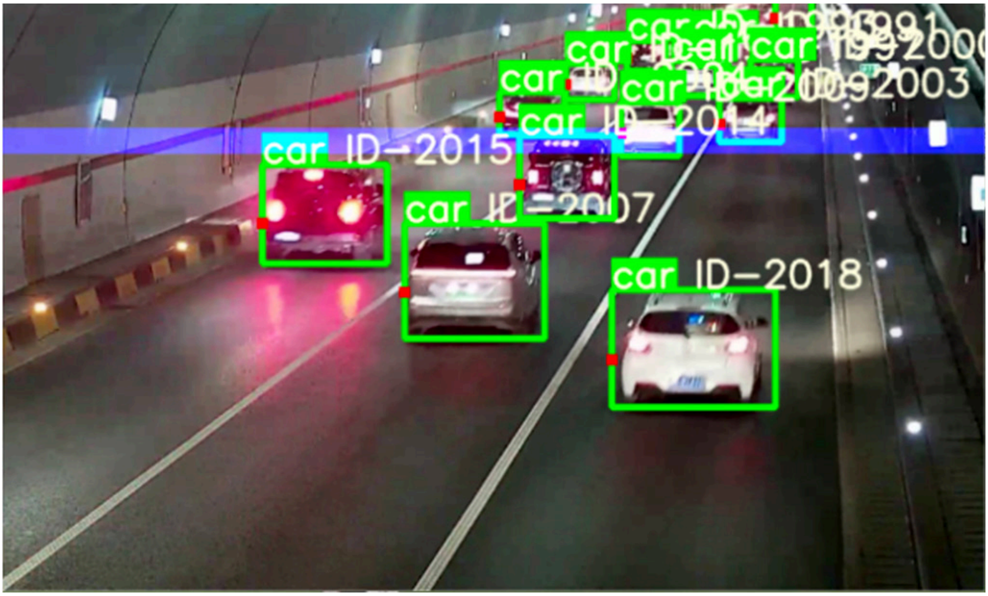

Figure 4. Vehicle counting by the bumping line method

3.2. Simulation scenario design

To verify the effectiveness of the VSL control strategy for the highway tunnel maintenance work zone proposed in this study, the traffic conditions of the VSL strategy are compared with those of the traditional SSL control method and verified using SUMO simulation software.

According to the "Safety Work Rules for Highway Maintenance" (JTG H30-2015) in China, the speed limit process in the tunnel maintenance work zone should be completed in the warning zone. Therefore, vehicles entering the tunnel maintenance work zone need to have completed all the deceleration and lane-changing operations by the time they reach the longitudinal buffer zone, so the scope of the study mainly focuses on the tunnel warning zone, the two upstream transition zones and their intervals, and the longitudinal buffer zone, as shown in Figure 5. Tunnel maintenance work zone road characteristics, traffic characteristics, and speed limit control sign information are entered into the simulation software SUMO to build a corresponding simulation of the tunnel maintenance work zone scene. The work zone of the tunnel maintenance project studied in this paper is a two-bore unidirectional traffic zone, and the construction zone is a partially closed single-lane construction zone with one lane closed on the outside. The length of the warning zone is about 1.2 km, the length of the upstream transition zone is 40 m, the length of the longitudinal buffer zone is 50 m, the length of the working zone is 500 m, the length of the downstream transition zone is 40 m, the length of the termination zone is 40 m, and the total length of the construction zone is 1.87 km. The speed control signs are set up in the warning zone, and one is set up at intervals of 300 m from the beginning of the warning zone. The system is established with a three-level speed limit, and nine speed control signs are set up for the sub-lanes. Each lane sets up a total of nine speed limit signs. A detector is set up at a distance after the speed limit sign and at the entrance of the work zone. The simulation scenario of the maintenance work zone is shown in Figure 6.

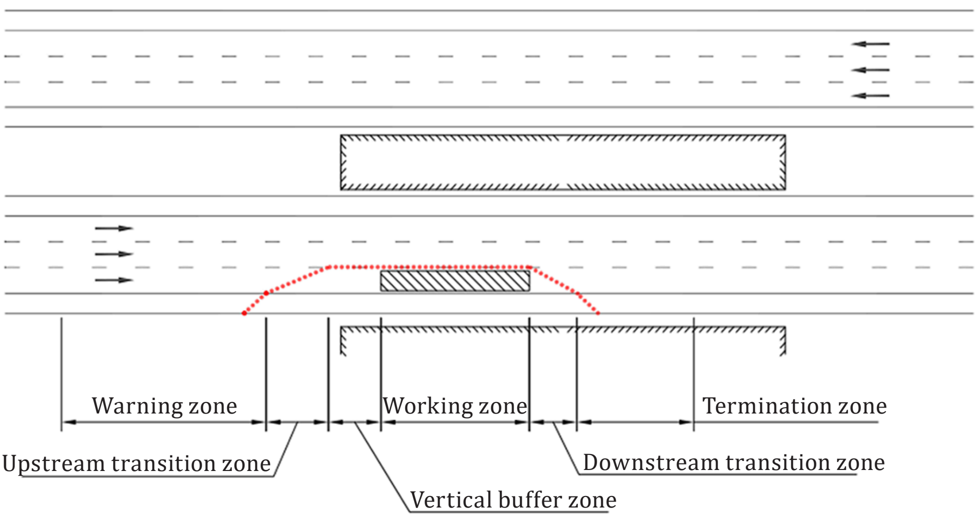

Figure 5. Maintenance work near the entrance of a two-bore, one-way tunnel

Figure 6. Schematic diagram of the SUMO simulation scene

In the simulation scenario, the total length of the simulation control is stipulated to be 4200 s, with the initial 600 s as the warm-up time to ensure stable traffic flow. Subsequently, it enters the MPC control phase with a control cycle of 300 s, during which the speed limit is updated in real-time based on the predicted state. Traffic state simulation under the traditional static control and VSL control is carried out, respectively, so as to compare the passing efficiency indices and traffic safety indices under the two situations and measure the reliability and effectiveness of the model. Based on the survey information of the work zone, traditional speed limit control does not divide the speed limit by lane; instead, it sets three levels of speed limits at 60 km/h, 50 km/h, and 40 km/h. In contrast, the NSGA-II optimisation control algorithm divides the speed limit by lane and dynamically updates the speed limit information according to the real-time traffic conditions.

After clarifying the experimental settings, such as simulation duration, control time domain, and traditional speed limit levels, it is further necessary to explain the key components of the MPC control framework, including performance evaluation of the predictive model and parameter setting of the multi-objective optimisation function. The XGBoost model is used to predict traffic flow, large vehicle rate, and average speed, with triple cross-validation accuracy of RMSE 71.94% and MAPE 7.57%, meeting the requirements of control algorithms for short-term prediction. At the same time, the multi-objective optimisation function in MPC is solved through the NSGA-II algorithm, and its weights are determined by an expert rating method based on the evaluation of ten domain experts, thus achieving a reasonable balance between safety and efficiency objectives. The weights are shown in Table 1.

Table 1. The weights of each objective in the multi-objective control function

Weight Coefficient	α	β	γ
Weight Value	0.4	0.4	0.2

3.3. Experiments and results

The changes of vehicle speed with spatial location in different cycles under traditional speed limit control and VSL control are shown in Figure 7, respectively. From Figure 7a), it can be seen that under the traditional speed limit control, the fluctuation of the speed value in space and cycle is more obvious, and the whole shows a large speed difference; the highest value of the speed is about 20.60 m/s, which is more concentrated in the distribution, and the peak speed area is smaller; the speed of some detecting points and cycles is significantly low, which shows a large localised congestion or uneven speed phenomenon. From Figure 7b) comparing the speed change under traditional speed limit control, it can be seen that under dynamic VSL control, the speed distribution is smoother and less fluctuating, and the highest value of the speed is increased to 22.60 m/s, which is a certain increase compared with Figure 7a), indicating that VSL control can improve the overall traffic efficiency; and the low-speed area is reduced, and the distribution of the speed at the various detection points tends to be more uniform, which indicates that the control scheme alleviates local congestion. The control scheme alleviates localised congestion. Overall, VSL control effectively reduces periodic and spatial speed fluctuations and improves the passage efficiency and stability of traffic flow.

a) No-VSL varying cycle speeds **b)** VSL varying cycle speeds

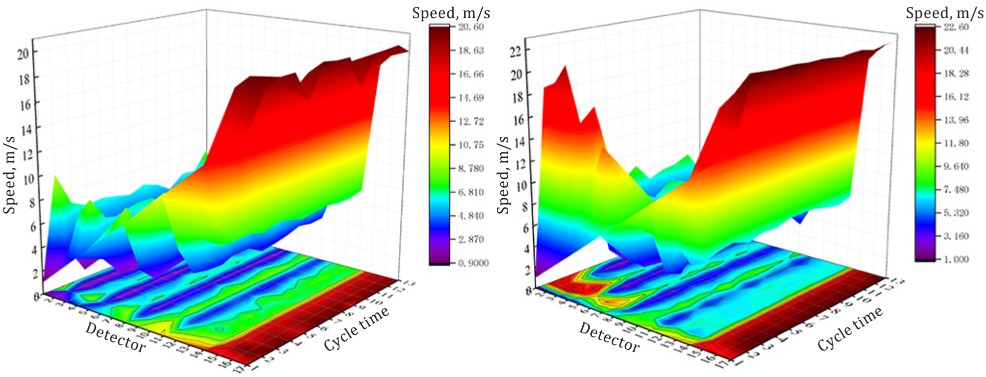

Figure 7. Plot of speed change in different cycles of no-VSL and VSL

3.3.1. Analysis of changes in traffic flow parameters during a single control cycle

In order to evaluate the effect of different speed limit schemes in a more detailed way, considering the speed limit settings of the sections in the maintenance work zone of the tunnel, three sections with a length of 300 m in the warning zone and the sections in the work zone are selected as the analysis intervals. Timely detection and control of congestion is the key to alleviating traffic congestion and ensuring driving safety, so the analysis time frame is taken as the first three cycles after the start of control. The vehicle speed changes in each analysis time range and analysis interval are shown in Figure 8. Meanwhile, to assess the effectiveness of lane-level control in the dynamic speed limit scheme, the change of vehicle speed over time for each lane is shown in Figure 9.

According to the data in Figure 8, at the beginning of the cycle in zones 1, 2, and 3, the vehicle speeds with the dynamic VSL scheme were significantly higher than those with the traditional SSL scheme. As the cycle progressed, the vehicle speeds under both schemes decreased and stabilised, but the average vehicle speed under the dynamic VSL was always higher than that under the conventional speed limit scheme. This suggests that the dynamic VSL scheme may allow higher vehicle speeds in the warning zone initially to effectively divert traffic flow but will then be adjusted according to traffic conditions and safety needs. In Zone 4, the speed variations are smoother, with the speeds under both speed limit schemes being similar at the beginning of the cycle and then remaining at a relatively stable level. This indicates that in the tunnel maintenance work zone, the traffic conditions tend to be stable, and a more consistent speed can be maintained for both the dynamic VSL and the traditional SSL.

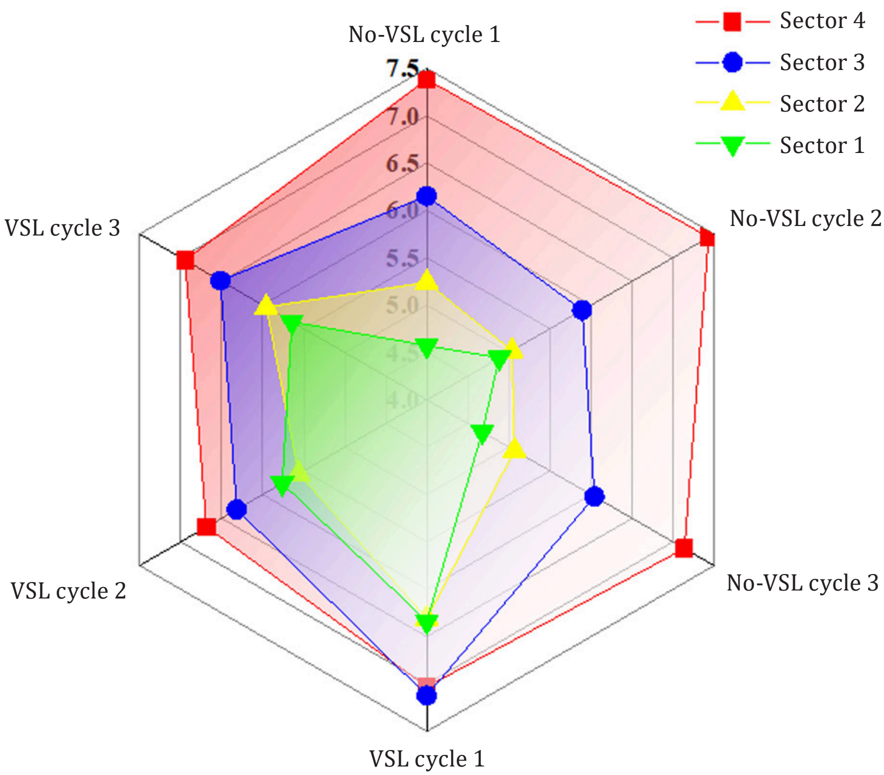

Figure 8. Effectiveness of controls at the sector level

After the occurrence of congestion, the vehicle speed slightly rebounds when the vehicle passes through the warning zone and approaches the work zone using traditional speed limit controls in Figure 9. However, the traditional speed limit scheme lacks flexibility, resulting in a slow and uneven speed recovery process. In contrast, with the VSL scheme, the speed increase is smoother and more significant. With the dynamic adjustment of the speed limit, the speed is guided more flexibly and effectively, which improves the overall smoothness and efficiency of the traffic.

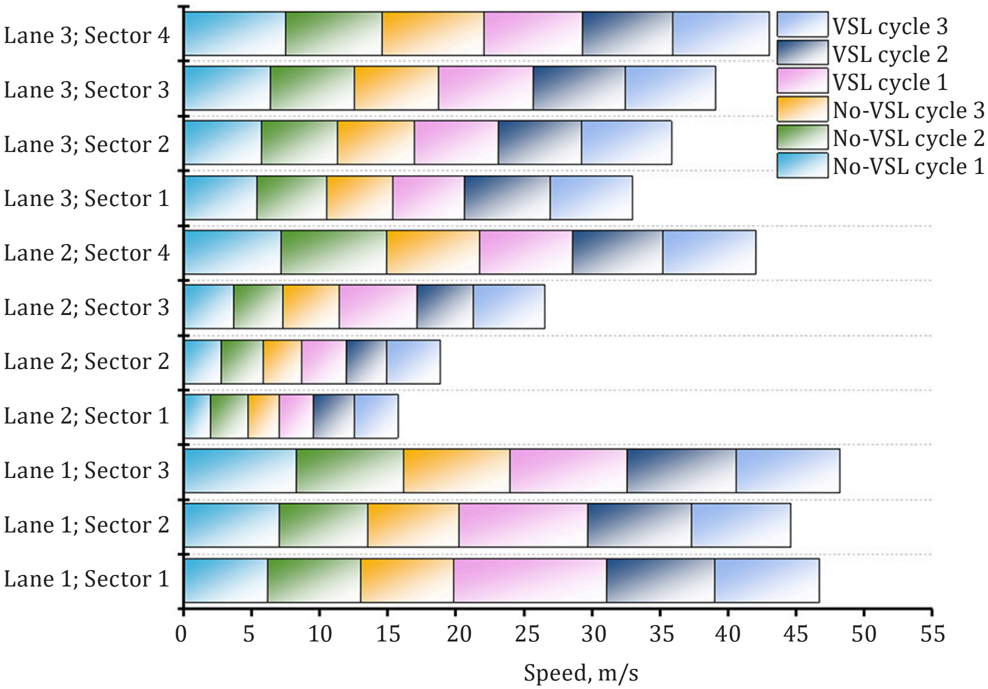

Figure 9. Lane-level control effects

After congestion occurs, because lane 1 and lane 2 are adjacent to each other, when vehicles enter the work zone from the warning zone, the vehicles on lane 1 will change lanes to lane 2 in advance, and this lane-changing behaviour leads to significantly lower speeds on lane 2 than on lane 3, which further exacerbates the imbalance of traffic flow. Under the traditional speed limit control scheme, the difference in vehicle speeds triggered by lane changing of vehicles on lane 1 is more significant, resulting in localised traffic congestion and affecting the overall smoothness, especially in the work zone section. Under the VSL control scheme, the speed limit system can dynamically adjust speeds based on real-time traffic flow and lane changes, which is an improvement over the traditional speed limit control scheme. Through flexible speed limit control, the VSL scheme effectively reduces the speed difference between different lanes and avoids unbalanced traffic flow due to early lane changes, thus enhancing the smoothness of traffic flow and overall traffic efficiency to a certain extent.

Both the traditional static speed control method and the NSGA-II optimization method enhance the safety and access efficiency of the maintenance work zone to different degrees. Simulation results show that the NSGA-II optimisation algorithm can obtain better speed limit control values, which in turn effectively improve the traffic efficiency and safety.

3.3.2. Analysis of changes in traffic flow parameters over multiple control cycles

During the first 12 cycles after opening the control, the average speed, speed standard deviation, and total flow change of the traffic flow through the whole simulation section in each cycle are shown in Figure 10, respectively. The evaluation indices of each control method within the total control duration (12 control cycles) are shown in Table 2.

Table 2. Assessment indicators under different methodologies

Methodology / Norm	Traditional SSL	Dynamic VSL
Total travel time, s	132 938	109 680
Total travel time reduction ratio, %	–	17.5
Speed standard deviation	1.3825	1.0773
Speed standard deviation reduction ratio, %	–	22.1
Traffic volume, vehicles/h	2373	2556
Proportion of increase in traffic volume, %	–	7.8

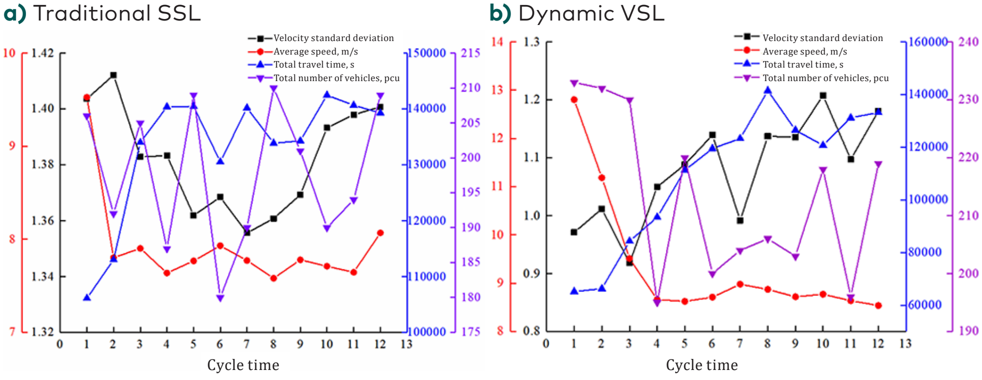

Figure 10. Indicators for cyclical assessment under different methodologies

As can be seen in Figure 10, the average speed under both speed limit methods decreases with the increase in control duration, but the average speed of vehicles under the dynamic VSL method is slightly higher than that under the traditional SSL, and the speed standard deviation is smaller. Combined with Table 1, the total flow of vehicles under the dynamic VSL method is improved by 7.8%, and the standard deviation of speed and total travel time are reduced by 22.1% and 17.7%, respectively. By implementing the NSGA-II-based dynamic VSL scheme in the tunnel maintenance work zone, the vehicles can drive through the tunnel maintenance work zone more quickly with smoother speed, and the traffic efficiency and safety are improved compared with the traditional SSL method.

Overall, dynamic VSL schemes may allow higher speeds at the beginning of the cycle and can make flexible adjustments according to the actual traffic conditions, especially in special road sections like tunnel maintenance work zones, providing better adaptability. In contrast, the traditional SSL scheme maintains a relatively fixed speed throughout the cycle, which is more stable but may lack flexibility in responding to unexpected traffic conditions. Therefore, road sections that require adjustments based on real-time traffic flow and safety requirements may benefit more from dynamic VSL schemes.

4. Discussion

The simulation results of this study indicate that the proposed dynamic MPC-VSL control strategy based on XGBoost prediction and NSGA-II optimisation can achieve differentiated speed limit updates for lanes and control cycles in tunnel maintenance work areas. Compared with traditional SSL, this method exhibits significant advantages in both efficiency and security metrics. Specifically, VSL reduces the average travel time of vehicles by about 17.5% and improves traffic capacity. At the same time, the standard deviation of inter-lane speed decreased by about 22.1%, effectively suppressing speed fluctuations and reducing the risk of rear-end collisions. These findings show that real-time and refined speed limit control is vital for safety and efficiency in high-risk, space-constrained tunnel maintenance zones.

Compared with existing research, Niu et al. (2022) proposed a VSL method based on multi-scenario rules for bottleneck areas on highways. The method mainly sets graded speed limits based on congestion level and meteorological conditions, and verifies that delays can be reduced by 10–20% under moderate traffic conditions. Unlike its rule-based and hierarchical control approach, this study emphasises dynamic regulation based on prediction and optimisation, especially suitable for the closed and high-risk special scenario of tunnels. Both indicate that a reasonable VSL strategy can significantly improve traffic efficiency and safety within a certain flow range. However, the results of this article further highlight the unique advantages and stronger adaptability of predictive-driven and optimisation methods in tunnel maintenance work areas, providing new ideas and practical references for traffic management in complex road environments.

Conclusions

This study takes the Tiantai Mountain Tunnel in Qinling Mountains as a case study and proposes a multi-objective VSL control strategy that combines nonlinear MPC and XGBoost prediction models. The simulation results show that this method can achieve a balance between total travel time, speed stability, and speed limit smoothness, and can flexibly adjust vehicle speed according to real-time traffic conditions, thereby effectively improving the traffic efficiency and operational safety of tunnel maintenance work zones.

However, the traffic flow in the tunnel maintenance work zone is highly complex and greatly affected by risk points and environmental factors. Existing research is still limited to the dimensions of efficiency and safety, and has not fully considered factors such as differences in driving behaviour and external environmental disturbances. In the future, features such as driving behaviour, weather, and emergencies will be further introduced, and optimisation objectives will be expanded to comfort and environmental benefits to enhance the robustness of control strategies and promote their application value.

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Disclosure Statement

We declare that have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Notations

Variables and functions

$v_{\min}$ – explanation of the lower limits of the design speed;

$v_{\max}$ – explanation of the upper limits of the design speed;

$v_j(t+k+1)$ – explanation of the speed limit value of the j speed limit sign at the moment $t+k+1$;

$v_j(t+k)$ – explanation of the speed limit value of the j speed limit sign at the moment $t+k$;

$v_{j+1}(t+k)$ – explanation of is the speed limit value of the $j+1$ speed limit sign at the moment $t+k$;

$a_{\min}$ – explanation of the maximum permissible deceleration;

$a_{\max}$ – explanation of the maximum permissible acceleration;

a_i – explanation of the acceleration of the i vehicle;

N^* – explanation of the set of positive integers.;

Q_{T} – explanation of total number of vehicles in the control cycle;

t_i – explanation of the travel time of the i vehicle in the control cycle;

v_i – explanation of the speed of the i vehicle in the control cycle;

$\bar{v}_T$ – the average speed of all vehicles in the control cycle.

Abbreviations

VSL – Variable Speed Limit,

MPC – Model Predictive Control,

NSGA-II – Non-dominated Sorting Genetic Algorithm II,

CTM – Cell Transmission Model,

ML – Machine Learning,

SSL – Static Speed Limit.