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Models for Optimizing Traffic Flow in Unmanned Mining Road Networks Based on High-precision Maps

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Abstract: This article proposed a high-precision map based traffic flow optimization model for unmanned mining road networks, aiming to optimize the flow of unmanned vehicles inside the mine through accurate map information and advanced algorithms, reduce traffic congestion, and improve transportation efficiency. By constructing high-precision maps and using graph theory and machine learning algorithms, the road network traffic flow of unmanned mining vehicles was optimized. The four experimental conclusions in the experimental stage indicated that the research model could effectively optimize the traffic flow of unmanned mining vehicles, and improve the efficiency and safety of mining operations. The effectiveness and practicality of the model were comprehensively validated through four experiments during the research phase. In the first road network efficiency evaluation experiment, the average speed of unmanned vehicles increased from 20 km/h to 30 km/h, and the average travel time decreased from 30 minutes to 20 minutes. In the traffic congestion experiment, the research model reduced the congestion relief time from 45 minutes to 25 minutes under high flow conditions of 150 vehicles per hour. In the dynamic route adjustment experiment, when encountering unexpected events, the optimized response time was reduced from 45 minutes for Event 1 to 30 minutes, and from 40 minutes to 25 minutes for Event 2. In the final safety performance evaluation experiment, the optimized accident rate decreased from 0.8 to 0.3; the number of violations decreased from 120 to 40; the number of emergency braking events also decreased from 90 to 30. From the data conclusion, it can be seen that the traffic flow optimization model for unmanned mining vehicles based on high-precision maps has shown significant effects in improving traffic efficiency, reducing congestion, enhancing dynamic route adjustment ability, and enhancing safety, fully verifying its application value in the process of mining automation and intelligence.

1. Introduction

The rapid development of mining automation technology has led to the increasing use of unmanned vehicles in mining transportation. However, the complex and ever-changing mining environment poses significant challenges to the optimization of road network traffic flow for unmanned vehicles. In order to optimize the road network traffic problem, this paper proposes a high-precision map based traffic flow optimization model for unmanned mining vehicles. The LSTM model can achieve dynamic optimization of vehicle driving paths and efficient management of traffic flow by accurately utilizing terrain and road condition information. This study has significant research significance and practical application value for improving the automation and intelligence level of mining operations.

In this article, an innovative road network traffic flow optimization model is developed for unmanned mining vehicles based on high-precision maps. In order to demonstrate the effectiveness of this model in improving traffic efficiency, reducing traffic congestion, flexibly adapting to route changes, and enhancing safety, four experiments are conducted during the experimental phase. The experimental results indicate that this optimization model can significantly enhance the operational efficiency and safety of autonomous vehicles, demonstrating its potential for practical applications.

At the beginning, the background and significance of research on optimizing mining traffic flow are introduced. Then, the challenges faced by autonomous vehicles in mining transportation are discussed, as well as the important role of high-precision maps in addressing operational efficiency and safety challenges. Next, the article provides a detailed explanation of the construction method and experimental design of the optimization model, including the evaluation of road network traffic efficiency, traffic congestion, dynamic route adjustment, and safety performance. On this basis, the article summarizes the research results and discusses the limitations of the model and future research directions.

2. Related Works

In existing research, many scholars have paid attention to the application of unmanned vehicles in mines and the optimization of traffic flow. For example, Huang Fucheng et al. established a new prediction model by combining genetic algorithm to improve the accuracy of ship traffic flow prediction [1]. Shen Y established a hard time window logistics distribution path optimization model under dynamic road networks, with the objective function of minimizing cost, for common urban logistics distribution models in the e-commerce environment [2]. The optimization model designed by Aleadelat W aimed to maximize the overall condition of the gravel road network, keeping the daily average traffic volume of each road unchanged [3]. In long-term analysis, optimizing the maintenance of large road networks is an extremely complex problem. Jooste F J proposed a fast and approximate alternative to traditional decision tree based strategy generation method [4]. Xing Qingsong classified impedance types based on the real-time status of the transportation network, and mathematically described the operational status and impedance degree of the network. He analyzed the time dependence characteristics of emergency delivery under the heterogeneity of network impedance, and proposed a time dependence calculation method [5]. Although these studies have made progress to some extent, most models have not fully considered the complexity and real-time changes of mining environments, resulting in limited optimization effects.

In previous studies, although various methods have been used to solve the traffic flow optimization problem of unmanned mining vehicles, these methods often overlook the importance of high-precision maps in mining traffic flow optimization. For example, Zhao Peng et al. studied the 5G communication network in the unmanned driving system of the 1703 level rail transport electric locomotive at Longshou Mine. They explained in detail the technical solution of 5G technology in the system by combining the on-site environment and application requirements, and explained the optimization measures for applying 5G technology in specific scenarios [6]. Currently, open-pit mines are moving towards the trend of informatization and unmanned development. Cheng Kunpeng proposed a solution based on unmanned driving technology to address the problem of low efficiency in traditional manual scheduling in open-pit mines [7]. Wu H et al. established a mechanical model for a certain type of mining vehicle as the research object. Through this model, it is possible to analyze the changes in the traction coefficient of vehicles when crossing obstacles [8]. Ribeiro R G proposed a new concise mixed integer linear programming model for solving the detection route and charging station planning problems of unmanned aerial vehicle belt conveyors [9]. Liu Minqiang proposed a solution to the problem of trajectory protection for unmanned transportation vehicles in open-pit mines, which addressed the susceptibility of perception fusion obstacle recognition methods in current unmanned driving technologies to weather and operational environments [10]. However, there is still insufficient exploration in the above studies on how to effectively utilize high-precision map information for traffic flow optimization. This article developed a new type of traffic flow optimization model for unmanned mining vehicles by constructing high-precision maps and combining advanced traffic flow theory and algorithms.

3. Methods

3.1 High-precision Map Construction

In the work carried out in mining areas, raw data should be collected through techniques such as ground measurement and aerial photography. High-precision map is machine oriented map data for autonomous vehicle. It is an electronic map of "high precision, high dynamic and multi-dimensional". It provides precise positioning at the centimeter level for vehicles, real-time dynamic path planning information, assists in decision-making paths, and provides detailed lane information, road component information, subdivision element information, and traffic safety information to help vehicles travel from their departure point to their destination. High-precision maps integrate multiple sensor data information, achieving effective safety redundancy and providing a global perspective for autonomous vehicles [11].

For autonomous vehicles, they require centimeter level accuracy for precise positioning, path planning, and decision-making in complex environments. Considering that the mining environment changes with mining activities, this update can be achieved through repeated ground measurements and aerial photography, as well as real-time data collection through sensors installed on unmanned vehicles. These high-precision maps are ultimately applied to road network traffic flow optimization models for autonomous vehicles, in order to predict traffic flow within mining areas and optimize vehicle driving paths.

3.2 Real-time Traffic Management Strategy

This chapter focuses on obstacle detection in complex environments of open-pit mining areas. Firstly, a dataset of driving obstacles in open-pit mining areas is constructed. Due to the lack of negative obstacles in the existing dataset, the positive obstacles are subdivided and new obstacle categories such as sharp road debris are added. Subsequently, in-depth research and analysis on mainstream object detection algorithms is conducted, focusing on the multi-scale and small target characteristics of obstacles in open-pit mining areas. The network model is extensively optimized to ensure the safe driving of unmanned mining vehicles [12-13].

In order to collect real-time traffic data, multiple sensor networks in the road network of the mine are deployed, including vehicle positioning devices, traffic flow monitors, and environmental monitoring equipment. These devices can provide real-time information on the operating status of vehicles, road usage, and environmental conditions. All of this data are sent to a central processing system and processed by a data analysis module to identify current traffic patterns and potential congestion points.

The traffic management system utilizes traffic flow prediction models and analysis results to calculate the optimal driving route and speed adjustment plan. These adjustment suggestions are sent in real-time to each unmanned vehicle through wireless communication systems. Vehicles that receive instructions automatically adjust their route or speed to avoid congested areas or to adapt to upcoming traffic flow changes. This mechanism ensures that unmanned vehicles can operate efficiently and safely within the mining area, while greatly improving the smoothness and responsiveness of the entire mining transportation system. Among them, the flow optimization function Q_{opt} can be used to adjust the flow direction and speed of the vehicle, as shown in Formula (1):

$$Q_{opt} = \max \sum_{i=1}^{N} w_i \cdot Q_i(t) \tag{1}$$

In Formula (1), $Q_i(t)$ represents the traffic flow at time t on the i-th road; w_i is a dynamically assigned weight based on the importance of the road and the current traffic situation; the total number of roads is N. In the event of an emergency, real-time traffic management strategies can respond quickly. The system immediately reassesses the traffic situation, adjusts traffic flow predictions, and updates the vehicle's driving route to minimize the impact of events on traffic flow.

3.3 Dynamic Road Network Management

In the dynamic road network management scheme, the real-time data collection system, traffic flow prediction model, dynamic route planning algorithm, and real-time traffic management strategy work closely together to build a comprehensive management framework. The operation of this framework began with the installation of sensors at key points in the mining road network, which are responsible for collecting information on the location, speed, and route selection of vehicles, as well as road condition data, such as congestion, construction areas, and temporary roadblocks [14].

In this system, traffic flow prediction models play a crucial role, which predicts the traffic flow of the mining road network at different time periods by analyzing real-time and historical data. This enables to not only monitor and respond to current traffic conditions in real-time, but also anticipate and plan future traffic flows, greatly improving the efficiency and safety of mining transportation.

The dynamic route planning algorithm utilizes the output of high-precision maps and prediction models to recommend the best path to unmanned vehicles. When road congestion, construction, or other unexpected events occur, algorithms can quickly adjust planning, guide vehicles to take detours or adjust their speed to reduce possible delays and risks. Among them, the distribution of traffic flow $f_{ij(t)}$ can be represented by Formula (2):

$$f_{ij(t)} = \frac{N_i(t)}{\sum_{k \in K} N_k(t)} \cdot D_j(t) \tag{2}$$

In Formula (2), traffic flow allocation $f_{ij(t)}$ represents the traffic flow from node i to node j at time t; $N_i(t)$ represents the number of vehicles at node i at time t; $D_j(t)$ is the demand of node j at time t; K is the set of nodes reachable from node i.

The dynamic road network management plan comprehensively considers strategies for responding to natural disasters, accidents, and other emergencies, and evaluates its effectiveness by analyzing actual operational data. The results show that this scheme significantly optimizes the transportation efficiency and safety of unmanned mining vehicles, effectively reduces traffic congestion, and improves the overall operation status of the road network.

4. Results and Discussion

4.1 Evaluation of Road Network Traffic Efficiency

The effectiveness of the optimization model for traffic flow of unmanned mining vehicles based on high-precision maps was evaluated in the evaluation experiment of road network traffic efficiency. The experiment tested the driving of 100 unmanned vehicles in the mining road network, and compared the average traffic speed and time before and after applying the optimization model. The traffic speed and time of each vehicle were plotted in a chart to visually display the differences before and after optimization.

Figure 1 (a) shows the speed comparison, and Figure 1 (b) shows the time comparison. From Figure 1, it can be seen that after applying the traffic flow optimization model, the average speed of unmanned mining vehicles increased from 20 km/h to 30 km/h, achieving a 50% increase in speed. Meanwhile, the average travel time decreased from 30 minutes to 20 minutes, with a 50% reduction in travel time. From the experimental data, it can be seen that by introducing a high-precision map based traffic flow optimization model for unmanned mining vehicles, not only does it significantly improve the average traffic speed of vehicles, but it also effectively shortens the travel time, as shown in Figure 1:

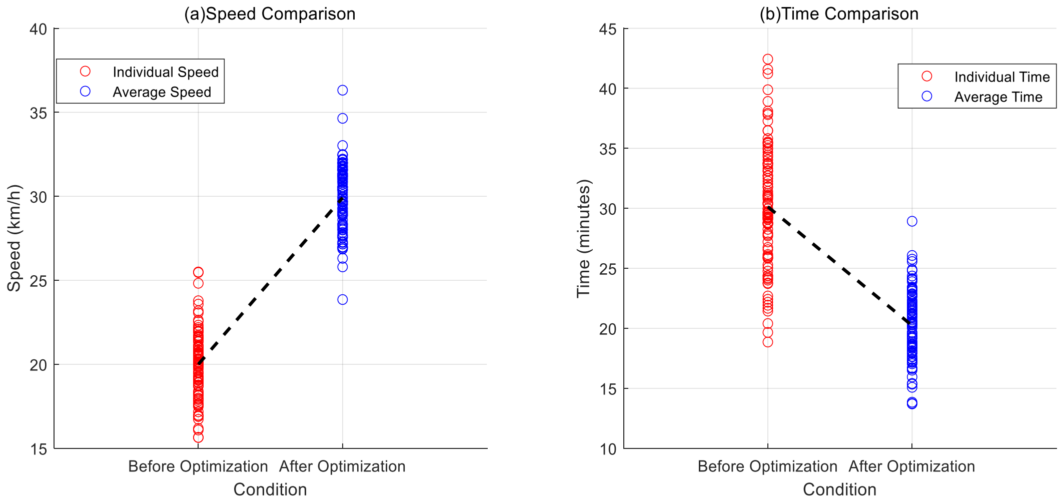

Figure 1: Evaluation of road network traffic efficiency

4.2 Evaluation of Traffic Congestion Situation

In the simulation experiment of traffic congestion, the optimization model based on high-precision maps was evaluated for its ability to alleviate congestion of unmanned mining vehicles under different flow conditions. The experiment was conducted at three different levels of vehicle flow: low, medium, and high, and then the congestion relief time was compared between unoptimized and optimized levels, as shown in Figure 2:

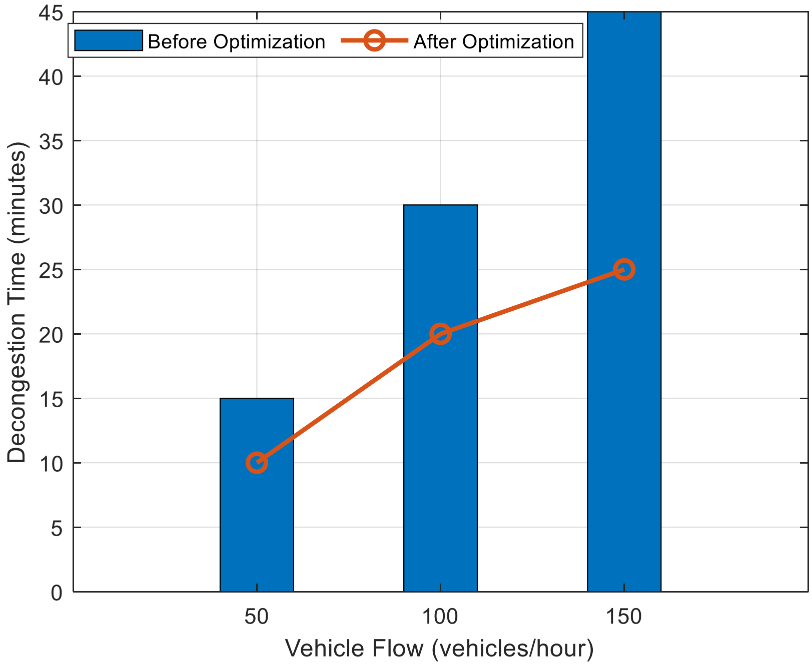

Figure 2: Evaluation of traffic congestion situation

From Figure 2, it can be seen that under the flow condition of 50 vehicles per hour, the congestion relief time was reduced from the unoptimized 15 minutes to 10 minutes; under the condition of 100 vehicles per hour, the congestion relief time was reduced from 30 minutes to 20 minutes; under the condition of 150 vehicles per hour, the congestion relief time was reduced from 45 minutes to 25 minutes. From the experimental data conclusion, it can be seen that the traffic flow optimization model for unmanned mining vehicles based on high-precision maps can effectively reduce traffic congestion under different flow conditions, which is of great significance for improving the efficiency and safety of mining logistics transportation.

4.3 Dynamic Route Adjustment Experiment

In the dynamic route adjustment experiment, the response ability of a high-precision map based mining unmanned vehicle traffic flow optimization model to emergencies was evaluated. The experiment was conducted under two common emergency conditions, road closures and speed restrictions, namely Event 1 and Event 2, to compare the total time required for vehicles to complete the established task before and after optimization. The time required for vehicles to complete tasks under two types of emergencies was plotted in a chart to visually demonstrate the differences before and after optimization.

From Figure 3, it can be seen that in the case of Event 1 facing road closure, the optimized response time decreased from 45 minutes to 30 minutes; in Event 2, when encountering a speed limit, the response time was reduced from 40 minutes to 25 minutes. From the above experimental data conclusions, it can be seen that the optimized model effectively improved the vehicle's adaptability to real-time changes in road conditions and significantly shortened the total time required to complete the task. The specific data situation is shown in Figure 3:

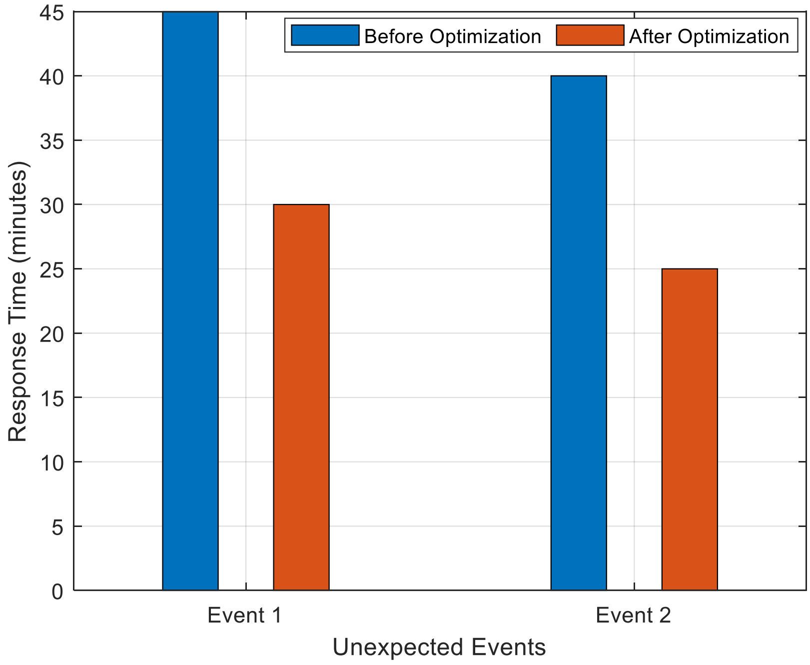

Figure 3: Dynamic route adjustment evaluation

4.4 Safety Performance Evaluation Experiment

In the safety performance evaluation experiment, the experiment verified how the optimization model based on high-precision maps can improve the safety performance of unmanned mining vehicles by reducing accident rates, the number of violations, and emergency braking events. In the experiment, the impact of the model on security performance improvement was quantified by comparing the data before and after optimization. The evaluation of accident rate AR can be expressed by Formula (3):

$$\mathrm{AR} = \frac{A}{V \cdot T} \times 10^{6} \tag{3}$$

In Formula (3), the total number of accidents that occurred during the observation period is A; V represents the number of vehicles; the total driving time is T. Multiplying by 10^6 is to standardize the accident rate to the number of accidents per million vehicle kilometers. The specific data details are shown in Table 1:

Table 1: Safety performance evaluation experiment

Safety Metrics	Before Optimization	After Optimization
Accident Rate	0.8	0.3
Violations Count	120	40
Emergency Braking Events	90	30

In Table 1, after optimizing the model, the accident rate decreased from 0.8 to 0.3; the number of violations decreased from 120 to 40; the number of emergency braking events also decreased from 90 to 30. From the data results, it can be seen that by using high-precision maps and traffic flow optimization techniques, accidents and potential safety risks can be effectively reduced, significantly improving the safe operation level of unmanned vehicles in complex mining environments.

5. Conclusions

In this study, a high-precision map based traffic flow optimization model for unmanned mining vehicles was developed, and the effectiveness of the model in enhancing the traffic efficiency of unmanned mining vehicles, dealing with traffic congestion, achieving dynamic route adjustment, and improving driving safety was comprehensively tested through four specific experiments. The results of the experimental stage showed that the research model can not only improve the traffic speed of vehicles and shorten travel time, but also demonstrate stronger adaptability and safety performance in the event of emergencies. Although some progress has been made, there are still limitations in the accuracy and applicability of the model in extreme weather conditions and complex terrain applications. In future work, it is planned to further optimize the model to enhance its robustness and explore a wider range of practical application scenarios to validate and expand the research findings. Meanwhile, considering that combining advanced technologies such as machine learning and deep learning may further improve the performance and application areas of the model, this article would also make efforts in this direction.

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