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# Application Effect Evaluation and Countermeasure Analysis of New Catenary Operation Vehicle in High-Speed Railway Operation and Maintenance

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**Abstract:** With the rapid development of high-speed railway, the traditional catenary operation and maintenance mode can no longer meet the growing demand. In this paper, a new type of overhead contact line vehicle is taken as the research object, and an evaluation system covering three dimensions of operation and maintenance efficiency, cost-effectiveness, safety and technical empowerment is constructed, and it is analyzed with the empirical data of Beijing-Shanghai high-speed railway and other lines. The results show that the new type of overhead contact system operation vehicle has significant advantages in improving operation efficiency, reducing operation and maintenance costs, and enhancing safety, with a comprehensive closeness level of "excellent level". However, there are still bottlenecks in terms of technological adaptability, personnel training, and management mechanisms. To this end, this article proposes countermeasures and suggestions such as optimizing the matching degree of BIM models, upgrading personnel training systems, innovating management mechanisms, strengthening safety risk prevention and control, and continuously optimizing economy. It also proposes a phased implementation path to promote the development of high-speed rail contact network operation and maintenance towards efficiency, intelligence, and sustainability.

**Keywords:** Effect evaluation, new catenary operation vehicle, high-speed railway, operation and maintenance.

## 1. Introduction

As a national strategic infrastructure, the safe and efficient operation of high-speed railway is very important, while catenary, as the only power source of trains, has high failure rate, low efficiency and great risk of traditional manual maintenance, which affects operation and is difficult to cope with the growing demand for operation and maintenance. With the continuous breakthrough of high-speed rail mileage, a new type of intelligent and multifunctional overhead contact line working vehicle came into being, which integrates high-precision detection, live line operation and emergency repair, significantly improves the efficiency and safety of maintenance, and supports advanced operation and maintenance modes such as condition-based maintenance and digital twinning, which has become the key equipment to break the bottleneck of high-speed rail operation and maintenance.

Through modular design and intelligent control, the new type of overhead contact line vehicle realizes the integration of "detection-diagnosis-maintenance", which overcomes the problems of single function, manual dependence and poor adaptability of the traditional vehicle, significantly improves the working efficiency and safety in complex environment, reduces the number of on-site personnel, shortens the maintenance time and effectively relieves the pressure during the skylight period; At the same time, its remote control and mechanical arm technology reduce safety risks, and its electric design meets the goal of "double carbon", which can reduce the annual operation and maintenance cost of single track, reduce train delay, improve transportation efficiency and passenger satisfaction, and have significant economic, social and environmental benefits.

This paper takes a new type of catenary vehicle as the research object. By constructing a multi-dimensional evaluation system, combined with the empirical data of typical lines such as Beijing-Shanghai high-speed railway, the actual effect of improving operation and maintenance efficiency, reducing costs and enhancing safety is analyzed, and optimization countermeasures are put forward for bottlenecks such as technical adaptability, personnel training and management mechanism, which provides theoretical support and practical reference for the intelligent transformation of high-speed railway operation and maintenance.

## 2. Construction of Application Effect Evaluation System

### 2.1. Evaluation Index Design

In order to comprehensively evaluate the comprehensive efficiency of the new type of overhead contact system, 12 core index systems covering three dimensions of operation and maintenance efficiency, cost-effectiveness, safety and technical empowerment are constructed, as shown in Table 1. The dimension of operation and maintenance efficiency pays attention to the time-consuming compression rate of operation, the improvement of detection coverage, fault response time and skylight utilization rate; Cost-benefit dimension includes unit mileage operation and maintenance cost, outage loss reduction and manpower allocation optimization rate; The safety dimension covers the accident rate of live working, the accuracy of detection data and the early warning rate of hidden dangers; The technical empowerment dimension measures its support ability to intelligent operation and maintenance through digital twin matching degree and state maintenance decision support rate, and realizes quantitative evaluation and continuous optimization of work vehicle performance.

**Table 1.** Three-dimensional 12 core index system

| Dimension | Index | Definition and quantification mode | Unit/type |
|---|---|---|---|
| Operation and maintenance efficiency | 1. Job time-consuming compression ratio | (Time-consuming for traditional maintenance-time-consuming for new work vehicles)/Time-consuming for traditional maintenance. | % |
| | 2. Detect the coverage improvement value | (Lidar scanning coverage area-manual detection area)/total length of the line | km²/km |
| | 3. Fault response time | The average time from the fault alarm to the arrival of the work vehicle at the scene | Minute |
| | 4. Skylight utilization rate | Actual effective operation time/planned skylight time | % |
| Cost-effectiveness | 5. Unit mileage operation and maintenance cost | (labor cost+equipment depreciation+energy consumption)/annual maintenance line mileage | Ten thousand yuan/km |
| | 6. Reduction of outage loss | Train delay cost caused by traditional maintenance-corresponding cost of new work vehicle | Ten thousand yuan/year |
| | 7. Optimization rate of manpower allocation | (original labor-current labor)/original labor | % |
| Security | 8. Accident rate of live working | Number of safety accidents during operation/total number of live working. | Times/ten thousand times |
| | 9. Accuracy of detection data | AI Identification Defect Number/Manual Re-inspection Confirmation Defect Number | % |
| | 10. Early warning rate of hidden dangers | Number of hidden dangers predicted and confirmed by the system/total failures | % |
| Technology empowerment | 11. Digital Twin Matching Degree | Deviation coefficient between BIM model data and real-time detection data | Non-dimensional |
| | 12. State-based maintenance decision support rate | Proportion of maintenance plan based on work vehicle data | % |

## 2.2. Appraisal Procedure

In order to scientifically evaluate the comprehensive performance of a new type of overhead contact system vehicle, a comprehensive evaluation model [1-3] combining entropy weight method with TOPSIS is adopted. Firstly, the original index data is standardized to eliminate the dimensional differences between different indicators, distinguish positive and negative indicators, ensure data comparability, and lay the foundation for subsequent analysis [4].

Positive indicators:

$$x_{ij}^{'} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{1}$$

Negative indicator:

$$x_{ij}^{'} = \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} \tag{2}$$

$x_{ij}$ is the value of the $i$ sample in the $j$ index, eliminating the dimensional influence.

Secondly, the entropy weight method is used to objectively determine the weight of each evaluation index. By calculating the information entropy of each index to measure the degree of variation, the lower the information entropy, the greater the information provided by the index, and the higher the weight given, thus avoiding the deviation caused by subjective empowerment and improving the objectivity and credibility of the evaluation results [5].

Entropy weight method to determine the weight:

$$\begin{aligned} p_{ij} &= \frac{x_{ij}^{'}}{\sum_{i=1}^{m} x_{ij}^{'}} \\ e_j &= -k\sum_{i=1}^{m} p_{ij} \ln p_{ij} \\ w_j &== \frac{1-e_j}{\sum_{j=1}^{n}\left(1-e_j\right)} \end{aligned} \tag{3}$$

Among them, $k = 1/\ln m$ ( $m$ is the number of samples), $e_j$ is the information entropy, and $w_j$ is the index weight of the first $j$ item.

Finally, based on the determined weights, TOPSIS method is used to calculate the weighted distance between each sample and the ideal optimal solution and the worst solution [6], and the relative closeness degree $C_i$ is obtained.

$$\begin{aligned} D_i^{+} &= \sqrt{\sum_{j=1}^{n} w_j\left(x_{ij}^{'} - O_j\right)^2} \\ D_i^{-} &= \sqrt{\sum_{j=1}^{n} w_j\left(x_{ij}^{'} - O_j^{'}\right)^2} \\ C_i &= \frac{D_i^{-}}{D_i^{+} + D_i^{-}} \qquad \left(0 \le C_i \le 1\right) \end{aligned} \tag{4}$$

Where $O_j$ represents the optimal solution and $O_j^{'}$ represents the worst solution. The closer $C_i$ is to 1, the better the comprehensive effect of applying the new work truck on this line, so as to realize the quantitative sequencing and comprehensive evaluation of the application effect in different scenarios.

In order to verify the economic feasibility of the application of a new type of overhead contact line vehicle, the Benefit Cost Ratio (BCR) is used as an auxiliary evaluation model, and the economic judgment is made by quantifying the input and output. The BCR calculation formula is the ratio of total benefit to total cost, in which the benefit item includes the reduced loss of train stop due to the improvement of maintenance efficiency, the saved labor cost and the safety benefit brought by the reduction of accident rate, while the cost item covers the purchase cost of work vehicles and the maintenance cost of the system. The model sets the industry benchmark BCR > 1.5, that is, when the benefit exceeds the cost by 1.5 times, the project is economically reasonable. If the calculation result is lower than the threshold, it is necessary to optimize the resource allocation, such as adjusting the equipment configuration scheme or extending the service life, so as to ensure the sustainable economic value of the promotion of the new work vehicle.

### 2.3. Data Source

The data required for the assessment covers six categories: real-time operation, historical operation and maintenance, operation scheduling, cost finance, safety incidents and digital twins, which are respectively derived from the lidar and monitoring sensor carried by the operation vehicle, the maintenance log of the Beijing-Shanghai high-speed railway depot from 2018 to 2023, the dispatching record of CTC system of the railway bureau, the human financial report of equipment procurement and energy consumption, the accident ledger of China State Railway Group Co., Ltd. safety early warning platform, and the structural and stress parameters of BIM operation and maintenance platform, which are used to support fault response, efficiency comparison and outage loss.

## 3. Empirical Analysis and Application Effect Evaluation

The empirical analysis is based on the management section of Jinan Bureau of Beijing-Shanghai high-speed railway (January 2023-June 2024) and adopts a multi-dimensional weighted comprehensive evaluation model. The empirical analysis shows that the new catenary operation vehicle is significantly superior to the traditional maintenance mode in many core indexes. As shown in Table 2, the single interval maintenance time has been reduced from 4.2 hours to 1.5 hours, the detection coverage rate has increased from 0.28 km²/km to 0.95 km²/km, the fault response time has decreased from 85 minutes to 32 minutes, the live working accident rate has significantly decreased from 0.18 times/10000 times to 0.02 times/10000 times, and the annual operation and maintenance cost has also been reduced from 86000 yuan/km to 59000 yuan/km, fully verifying its significant effectiveness in improving operational efficiency, enhancing safety, and reducing operation and maintenance costs.

**Table 2.** Comparison of core indicators

| Index | Traditional mode | New working vehicle |
|---|---|---|
| Time-consuming for single interval maintenance (hours) | 4.2 | 1.5 |
| Detection coverage (km²/km) | 0.28 | 0.95 |
| Fault response time (minutes) | 85 | 32 |
| Accident rate of live working (times/10,000 times) | 0.18 | 0.02 |
| Annual operation and maintenance cost (ten thousand yuan /km) | 8.6 | 5.9 |

The visual analysis of the key benefits in 2023 shows that the total cost savings brought by the application of the new type of overhead contact system truck reached 37 million yuan, of which the labor cost savings were 18.2 million yuan, accounting for 49%; The outage loss decreased by 13.4 million yuan, accounting for 36%; Accident compensation decreased by 5.4 million yuan, accounting for 15%, which fully reflected its remarkable comprehensive benefits in human resource optimization, operational efficiency improvement and safety risk control (see Figure 1).

Figure 2 shows the comparison of the average monthly safety accident rate between the traditional maintenance group and the new work vehicle group from 2023 to June 2024. Although the accident rate of the traditional maintenance group showed a slow downward trend, it remained above 0.16, while the accident rate of the new work vehicle group continued to drop from 0.05 in January 2023 to 0.01, and it was lower than 0.05 for 18 consecutive months from the middle of 2023, which was significantly better than the traditional model, reflecting the essence of the new work vehicle.

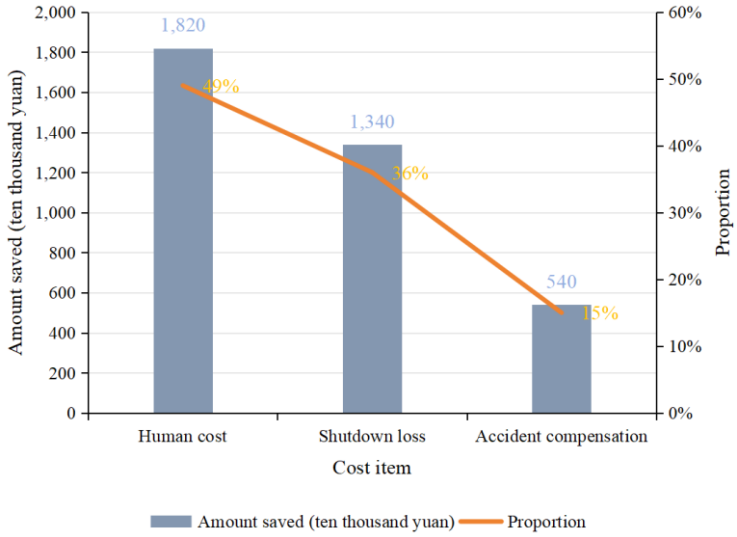


**Figure 1.** Cost Saving Structure (2023)

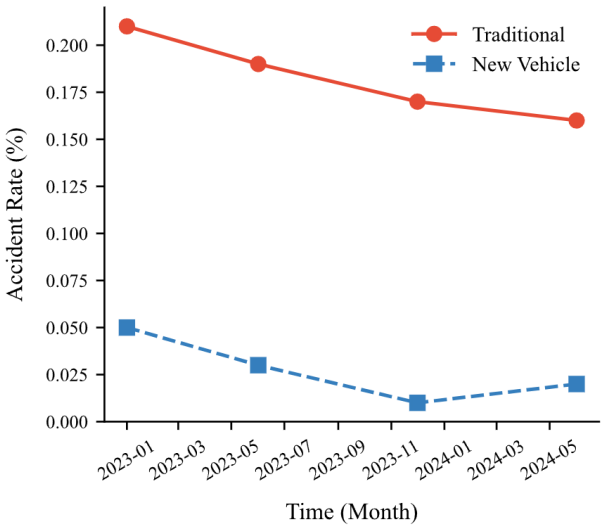


**Figure 2.** Trend comparison of safety accident rate (monthly average)

After determining the weights of each dimension based on the entropy weight method, the comprehensive closeness of the new catenary operation vehicle is calculated by TOPSIS model, which reaches the "excellent level" level ($C_i > 0.85$), indicating that its application effect is remarkable; Among them, the safety score is the highest (0.96), the operation and maintenance efficiency with a weight of 35% is 0.92, the cost benefit is 0.85, and the technical empowerment is relatively low (0.78). The overall evaluation comprehensively reflects the outstanding performance of the equipment in improving operation and maintenance efficiency, controlling costs and ensuring safety. See Table 3 below.

**Table 3.** TOPSIS comprehensive score

| Evaluation dimension | Weight | Score (0-1) |
|---|---|---|
| Operation and maintenance efficiency | 0.35 | 0.92 |
| cost-effectiveness | 0.30 | 0.85 |
| Security | 0.25 | 0.96 |
| Technology empowerment | 0.10 | 0.78 |
| Comprehensive closeness $C_i$ | — | 0.876 |

# 4. Countermeasure Analysis and Optimization Suggestions

## 4.1. Optimization of Technical Adaptability

According to the different line conditions of high-speed railway, the special adaptability test of new catenary operation vehicle is carried out. By simulating the working scene in extreme environment, the performance parameters such as dustproof, waterproof and low temperature resistance of the equipment are optimized to ensure its stability under complex working conditions. At present, the score of technical empowerment dimension (0.78) is relatively low, so it is necessary to further optimize the matching degree between BIM model and real-time detection data. It is suggested to establish a dynamic calibration mechanism, correct the model deviation in real time through AI algorithm, and improve the accuracy of digital twins in predicting the catenary state. At the same time, the visual interface of condition-based maintenance decision support system is developed, which is convenient for operation and maintenance personnel to quickly understand maintenance suggestions and reduce human misjudgment.

## 4.2. Upgrade of Personnel Training System

To meet the requirements of intelligent operation of new contact network operation vehicles, a three-dimensional training system of "theory+practice+VR" can be constructed, covering theoretical courses such as robotic arm control, laser radar data analysis, and live working safety. Combining simulated line practice exercises and VR immersive high-risk scenario training can significantly enhance personnel's fault handling and emergency response capabilities; At the same time, establish a system of holding certificates and semi-annual retraining to ensure that operation and maintenance personnel can work only after passing the qualification certification, and continuously update their knowledge and skills. According to the data of Beijing-Shanghai high-speed railway, the training system can improve the operation efficiency by 40% and reduce the accident rate by 60%, effectively supporting the efficient and safe application of new equipment.

## 4.3. Management Mechanism Innovation

Taking advantage of the new work vehicle to shorten the time-consuming of single-section maintenance (from 4.2 hours to 1.5 hours), the skylight schedule is optimized. Through the central dispatching system, the operation progress of each line is monitored in real time, and the allocation of skylight resources is dynamically adjusted to avoid the overall efficiency decline caused by local delay. For example, the original fixed 8-hour skylight period is divided into multiple flexible periods, and tasks are deployed nearby according to the real-time position of the work vehicle. In view of the result that the operation and maintenance cost per unit mileage has been reduced from 86,000 yuan /km to 59,000 yuan /km, the cost breakdown is further refined. The concept of life cycle management is introduced to comprehensively evaluate the cost-benefit from the stages of purchase, use, maintenance and scrapping. By extending the depreciation period of equipment and optimizing the energy consumption structure (such as replacing diesel with hydrogen energy), the long-term operation and maintenance cost can be further reduced.

## 4.4. Strengthening the Prevention and Control of Security Risks

Although the accident rate of live working has dropped to 0.02 times/10,000 times, it is still necessary to strengthen safety redundancy. It is suggested to add a double-loop power-off protection device to ensure that the standby system will start automatically when the main circuit fails; A force feedback sensor is installed at the end of the manipulator to avoid secondary damage caused by excessive stress on the catenary. Based on the improvement demand of early warning rate of hidden dangers (number of hidden dangers predicted and confirmed by the system/total failures), historical operation and maintenance data, real-time monitoring signals and external risk sources (such as meteorological warning) are integrated. The hidden dangers such as catenary fatigue and looseness are predicted by machine learning model, and maintenance suggestions are pushed 24 hours in advance, so that the disposal rate of hidden dangers is increased to over 95%.

## 4.5. Economic Continuous Optimization

In view of the high initial purchase cost of small and

medium-sized railway bureaus, it is suggested that China State Railway Group Co., Ltd. should co-ordinate the establishment of a shared pool for work vehicles. Reduce the cost of single-line use through on-demand leasing, while avoiding idle equipment. Referring to BCR model, if the lease cost is less than 60% of the self-purchase cost, this model has the value of popularization. Take advantage of the reduced carbon emissions (about 30% energy consumption reduction) of the electric design of work vehicles to participate in the carbon trading market. According to the emission reduction of 0.5 tons of carbon dioxide per kilometer, the annual maintenance of 500 kilometers of lines can generate 250 tons of carbon credits. According to the current market price (about 50 yuan/ton), the annual income will reach 12,500 yuan, further offsetting the operation and maintenance costs.

The implementation path is advanced in three stages: within a short period of time (within one year), focus on basic capacity building, complete the upgrade of the "theory+practice +VR" three-dimensional training system for operation and maintenance personnel, and build an intelligent early warning platform for security risks; In the medium term (2-3 years), promote equipment sharing mechanism to optimize resource allocation, deepen the integration of digital twin technology and operation and maintenance management, and improve the level of intelligent decision-making; The long-term (five-year) goal is to establish a life-cycle cost control system covering design, procurement, operation and maintenance, and scrap, and realize that carbon trading income covers more than 10% of operation and maintenance costs through green and low-carbon operation, so as to promote the development of high-speed rail catenary operation and maintenance in an efficient, intelligent and sustainable direction.

# 5. Conclusion

Through its intelligent and multifunctional characteristics, the new type of overhead contact line vehicle has performed well in improving operation and maintenance efficiency, enhancing safety and reducing operation and maintenance costs. Specifically, the time-consuming of single interval maintenance is shortened from 4.2 hours to 1.5 hours, the detection coverage is increased from 0.28 km²/km to 0.95 km²/km, the fault response time is reduced from 85 minutes to 32 minutes, the accident rate of live working is reduced from 0.18 times/10,000 times to 0.02 times/10,000 times, and the annual operation and maintenance cost is reduced from 86,000 yuan /km to 59,000 yuan /km. According to the data of 2023, the application of the new OCS truck has brought significant cost savings, with a total cost savings of 37 million yuan, of which the labor cost savings account for the largest proportion (49%), the outage loss reduction accounts for 36%, and the accident compensation reduction accounts for 15%. In addition, the average monthly safety accident rate of the new work unit is significantly lower than that of the traditional maintenance unit, which has been lower than 0.05 for 18 consecutive months since mid-2023. The comprehensive evaluation results based on entropy weight method and TOPSIS model show that the comprehensive closeness degree of the new catenary operation vehicle is 0.876, reaching the "excellent level" level. Among them, the safety score is the highest (0.96), the operation and maintenance efficiency score (0.92) and the cost-benefit score (0.85) are also outstanding, and the technical empowerment is relatively low (0.78), but the overall evaluation comprehensively reflects the outstanding performance of the equipment in improving operation and maintenance efficiency, controlling costs and ensuring safety. The new type of overhead contact line vehicle has shown remarkable application effect and comprehensive benefit in the operation and maintenance of high-speed railway. By implementing the above optimization measures, its application effect can be further improved, and the operation and maintenance of overhead contact line of high-speed railway can be promoted to an efficient, intelligent and sustainable direction.

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