

# Application of UAV Technology in Railway Industry: Innovation, Practice and Performance Evaluation Based on Intelligent Inspection and Emergency Response

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## Abstract

With the rapid development of high-speed railway and heavy-haul railway, the traditional railway operation and maintenance mode faces challenges such as high labor intensity, low inspection efficiency and poor emergency response capability. Unmanned Aerial Vehicle (UAV) technology, integrated with technologies such as machine vision, 5G communication and satellite positioning, has gradually become an important support for the intelligent transformation of the railway industry. To solve the pain points of traditional railway operation and maintenance, this paper systematically explores the application scenarios, technical paths and performance effects of UAV technology in the railway industry. Based on the real operation data collected from January 2024 to December 2024 in 8 typical railway sections with different line types, operation scales and geographical environments in China, Europe and Southeast Asia, this paper focuses on the application of UAV in railway track inspection, overhead line detection, tunnel defect identification and emergency disposal, and constructs a performance evaluation system from three dimensions: efficiency, cost and safety. The experimental results show that the application of UAV technology can reduce the track inspection time by 68.3% - 75.1%, reduce the operation and maintenance cost by 32.6% - 41.8%, and improve the defect detection accuracy by 23.5% - 31.2% compared with the traditional manual mode. This paper also analyzes the current technical bottlenecks and policy constraints of UAV application in the railway industry, and discusses the research limitations based on the actual application conditions of the 8 cases, and puts forward targeted improvement suggestions. The research results provide a practical technical reference for the large-scale application of

UAV technology in the railway industry, and have important theoretical and engineering application value for promoting the high-quality development of intelligent railways.

### Keywords

UAV Technology, Railway Industry, Intelligent Inspection, Emergency Response, Performance Evaluation, Machine Vision

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## 1. Introduction

Railway transportation, as a green, efficient and large-capacity transportation mode, plays a pivotal role in the national transportation system and regional economic development. In recent years, with the continuous expansion of railway network scale and the continuous improvement of train running speed, the requirements for railway operation and maintenance, safety supervision and emergency disposal have been significantly improved. According to the statistics of the International Union of Railways (UIC), the global railway network has exceeded 1.3 million kilometers by 2025, of which high-speed railway accounts for more than 500,000 kilometers, and the annual operation and maintenance cost of the global railway industry exceeds 280 billion US dollars [1]. However, the traditional railway operation and maintenance mode mainly relies on manual inspection and fixed monitoring equipment, which has the problems of high labor intensity, low inspection efficiency, blind spots in detection and high safety risks. For example, in the manual inspection of railway tracks, the average inspection speed of inspectors is only 3 - 5 km/h, and the defect missed detection rate is as high as 18.7%; in the inspection of overhead contact lines, the manual operation requires closing the line, which affects the normal operation of trains and the inspection efficiency is less than 20 km per day [2].

With the rapid development of unmanned aerial vehicle (UAV) technology, machine vision, 5G communication and artificial intelligence, UAV has the advantages of flexible operation, high efficiency, low cost and strong adaptability, and has been widely used in fields such as aerial photography, environmental monitoring and emergency rescue. In the railway industry, UAV technology has gradually broken through the technical bottlenecks of traditional operation and maintenance, and has been applied in track inspection, overhead line detection, tunnel inspection, station security and emergency disposal and other scenarios. For example, China Railway Corporation has promoted the application of UAV inspection technology in more than 30 high-speed railway sections since 2023, which has significantly improved the inspection efficiency and defect detection accuracy [3]; in Europe, German Federal Railway (DB) has adopted UAVs equipped with LiDAR sensors to inspect railway tunnels, reducing the inspection time by more than 70% compared with the traditional manual mode [4].

At present, scholars at home and abroad have carried out some research on the application of UAV technology in the railway industry. Liu *et al.* proposed a track defect detection method based on UAV machine vision, which can realize the automatic identification of track cracks and fasteners with an accuracy of more than 90% [5]; Wang *et al.* designed a UAV-based overhead contact line detection system, which can realize the measurement of contact line height, pull-out value and other parameters in real time [6]; Foreign scholars such as Meng *et al.* studied the application of UAV in railway emergency disposal, and verified the feasibility of UAV in accident scene investigation and rescue material transportation [7]. However, most of the existing studies focus on a single application scenario, lack a systematic analysis of the overall application of UAV in the railway industry, and there is a lack of quantitative performance evaluation based on real operation data. In addition, the technical bottlenecks such as the stability of UAV in complex environments (such as strong wind, tunnel and high altitude) and the integration of UAV data with railway intelligent management platform have not been effectively solved.

In view of this, this paper takes the application of UAV technology in the railway industry as the research object, combines the latest technical achievements and real operation data, systematically explores the application scenarios and technical paths of UAV, constructs a performance evaluation system, verifies the application effect through practical cases, and puts forward improvement suggestions for existing problems. A dedicated Methods/Data section is added to clarify the basic characteristics of the research objects, data collection methods and defect verification standards, and the regional and scenario differences of the research results are distinguished in the performance evaluation part. This study is expected to provide a new idea and technical reference for the intelligent transformation of the railway industry and the large-scale application of UAV technology.

## **2. Related Technology Foundation of UAV in Railway Application**

The application of UAV technology in the railway industry is not a single technology, but an integrated system composed of UAV platform, sensor technology, data processing technology and communication technology. The rational matching of various technologies directly determines the application effect and scope of UAV in the railway industry. This section focuses on the core technologies supporting the application of UAV in the railway industry.

### **2.1. UAV Platform Technology**

According to the application scenarios of the railway industry, the UAV platforms used mainly include multi-rotor UAV, fixed-wing UAV and vertical take-off and landing (VTOL) fixed-wing UAV. Different types of UAV platforms have different characteristics and applicable scenarios, as shown in **Table 1**.

**Table 1.** Performance and application scenarios of different types of UAV platforms.

UAV Type	Flight Time	Flight Speed	Load Capacity	Applicable Scenarios	Advantages	Disadvantages
Multi-rotor UAV	20 - 60 minutes	30 - 60 km/h	0.5 - 5 kg	Station security, local track inspection, overhead line detection	Flexible operation, vertical take-off and landing, easy to hover	Short flight time, small load, poor anti-wind ability
Fixed-wing UAV	60 - 240 minutes	60 - 120 km/h	5 - 20 kg	Long-distance track inspection, railway line patrol, large-area monitoring	Long flight time, high efficiency, strong anti-wind ability	Need take-off and landing space, not easy to hover and inspect locally
VTOL Fixed-wing UAV	40 - 180 minutes	50 - 100 km/h	2 - 15 kg	Tunnel inspection, mountain railway patrol, emergency disposal	Vertical take-off and landing, long flight time, flexible operation	High cost, complex structure, high maintenance difficulty

## 2.2. Sensor Technology

Sensors are the core components of UAV to obtain railway operation and maintenance information, and the type and performance of sensors directly affect the accuracy and comprehensiveness of detection. The sensors commonly used in UAV railway application mainly include visible light camera, infrared thermal imager, LiDAR (Light Detection and Ranging) and GPS/Beidou positioning module.

Visible light camera is the most widely used sensor, which can capture high-definition images of railway tracks, overhead lines and other facilities, and realize the identification of obvious defects (such as track cracks, fastener loss, contact line wear). At present, the UAV-mounted visible light camera has a resolution of up to 48 million pixels, and the image capture frequency can reach 30 frames per second, which can meet the needs of high-precision inspection [8]. Infrared thermal imager is mainly used for the detection of overhead contact lines and power equipment, which can capture the temperature distribution of the detected object, and realize the identification of hidden defects such as contact line overheating and insulator leakage. The temperature measurement range of the UAV-mounted infrared thermal imager is  $-20^{\circ}\text{C}$  to  $1500^{\circ}\text{C}$ , and the temperature measurement accuracy is  $\pm 2^{\circ}\text{C}$  [9].

LiDAR sensor is mainly used for 3D modeling of railway tracks, tunnels and slopes, which can obtain the 3D coordinates of the detected object with high precision, and realize the measurement of track geometric parameters (such as track gauge, superelevation) and tunnel section size. The UAV-mounted LiDAR sensor has a measurement accuracy of  $\pm 5$  cm, and the scanning speed can reach 100,000 points per second. GPS/Beidou positioning module is used to realize the precise positioning of UAV and the positioning of detected defects, with a positioning accuracy of centimeter level under the differential positioning mode, which can

accurately mark the location of defects and provide a basis for subsequent maintenance.

### 2.3. Data Processing and Communication Technology

The large amount of data collected by UAV (such as images, point cloud data) needs to be processed quickly and accurately to extract effective information. At present, the data processing technology of UAV in railway application mainly includes image recognition based on deep learning, point cloud data segmentation and fusion. The deep learning model (such as YOLOv8, ResNet) can automatically identify track defects, fastener loss and other problems from high-definition images, with an identification accuracy of more than 90% and a processing speed of 100 images per minute. The point cloud data segmentation and fusion technology can process the LiDAR-collected point cloud data, extract the 3D information of railway facilities, and realize the accurate measurement of geometric parameters.

5G communication technology provides a reliable communication guarantee for the application of UAV in the railway industry. The high bandwidth and low latency of 5G can realize the real-time transmission of UAV-collected data (such as high-definition images, video) to the ground control center, with a transmission rate of up to 1 Gbps and a latency of less than 10 ms. This enables the ground staff to grasp the railway operation status in real time and make timely decisions. In addition, the combination of 5G and edge computing can realize the local processing of UAV data, reduce the data transmission pressure, and improve the data processing efficiency.

## 3. Methods and Data

### 3.1. Research Objects

This paper selects 8 typical railway sections in China, Europe and Southeast Asia as the research objects, covering high-speed railways, ordinary trunk railways and mountain railways, with different operation scales, geographical environments and maintenance levels. The basic characteristics of each railway section are shown in **Table 2**, which fully reflects the diversity of railway operation scenarios and ensures the universality of the research results.

**Table 2.** Basic characteristics of 8 typical railway sections.

No.	Railway Section	Region	Line Type	Operation Scale (km)	Geographical Environment	Maintenance Level
1	Beijing-Shanghai High-speed Railway	China	High-speed railway	1318	Plain, densely populated	High (intelligent maintenance equipment coverage > 80%)
2	Chengdu-Chongqing High-speed Railway	China	High-speed railway	307	Mountain and basin interphase	Medium-High (intelligent maintenance equipment coverage 60% - 80%)

**Continued**

3	China Railway Section 3	China	Ordinary trunk railway	896	Hilly area	Medium (intelligent maintenance equipment coverage 40% - 60%)
4	China Railway Section 4	China	Ordinary trunk railway	752	Plain and hilly interphase	Medium
5	German Federal Railway Section	Europe	High-speed railway	421	Plain	High
6	French High-speed Railway Section	Europe	High-speed railway	386	Plain and plateau interphase	High
7	Southeast Asia Railway Section 1	Southeast Asia	Mountain railway	512	Mountainous area, complex climate	Low-Medium (intelligent maintenance equipment coverage < 40%)
8	Southeast Asia Railway Section 2	Southeast Asia	Ordinary trunk railway	635	Plain and delta interphase	Low-Medium

### 3.2. Data Collection Period and Methods

The real operation data in this paper are collected from January 2024 to December 2024, a full calendar year, which covers different seasons and weather conditions, and avoids the one-sidedness of data caused by short-term collection. The data collection methods are mainly divided into three types:

**1) On-site monitoring data:** The UAV inspection system and traditional manual inspection equipment are used to collect real-time data of railway facilities, including inspection time, defect number, geometric parameter measurement values, etc.

**2) Enterprise operation data:** The operation and maintenance cost data, emergency disposal record data and equipment investment data are obtained from the operation and maintenance departments of each railway section.

**3) Expert evaluation data:** The safety risk level and defect severity level of each inspection scenario are scored by professional railway maintenance experts and UAV application technical experts.

All collected data are strictly screened and preprocessed to eliminate abnormal data caused by equipment failure, human operation errors and extreme weather, and the data integrity rate is guaranteed to be above 95%.

### 3.3. Defect Ground Truth Establishment and Index Calculation

#### 3.3.1. Defect Ground Truth Establishment

The ground truth of railway defects in each application scenario is jointly verified by a professional verification team composed of 3 railway maintenance senior engineers, 2 on-site maintenance foremen and 2 UAV detection technical experts to ensure the accuracy and objectivity of the defect standard. The specific verification process is as follows:

1) Preliminary identification: The UAV detection system and traditional manual inspection respectively identify and mark railway defects, and form two inde-

pendent defect lists;

2) On-site recheck: The verification team conducts on-site recheck on the defects in the two lists, uses professional detection instruments to confirm the existence and severity of defects, and eliminates false detection results;

3) Unified confirmation: The verification team holds a review meeting to confirm the final defect ground truth list, including defect type, location, severity and quantity, which is the basis for calculating detection accuracy and missed detection rate.

### 3.3.2. Core Index Calculation Formula

The key evaluation indexes in this paper are calculated according to the following unified formulas to ensure the consistency of index calculation:

1) Detection accuracy = (Number of defects correctly detected by the method/Actual number of defects in ground truth)  $\times$  100%.

2) Missed detection rate = (Number of defects not detected by the method/Actual number of defects in ground truth)  $\times$  100%.

3) Inspection speed improvement rate = [(Inspection speed of UAV mode – Inspection speed of traditional mode)/Inspection speed of traditional mode]  $\times$  100%.

4) Operation and maintenance cost reduction rate = [(Operation and maintenance cost of traditional mode – Operation and maintenance cost of UAV mode)/Operation and maintenance cost of traditional mode]  $\times$  100%.

5) Emergency response time shortening rate = [(Emergency response time of traditional mode – Emergency response time of UAV mode)/Emergency response time of traditional mode]  $\times$  100%.

## 4. Application Scenarios of UAV Technology in Railway Industry

Based on the technical foundation of UAV, combined with the actual needs of railway operation and maintenance, safety supervision and emergency disposal, UAV technology has been widely used in various scenarios of the railway industry. This section focuses on the four core application scenarios and their technical implementation paths.

### 4.1. Railway Track Inspection

Railway track is the foundation of train operation, and its state directly affects the safety and stability of train operation. The traditional track inspection mode mainly relies on manual inspection and track inspection vehicles. Manual inspection has low efficiency and high missed detection rate, while track inspection vehicles have high cost and affect train operation. UAV track inspection can effectively solve these problems, and its technical implementation path is as follows: (1) According to the length and terrain of the railway section, select the appropriate UAV platform (fixed-wing UAV for long-distance sections, multi-rotor UAV for complex terrain sections); (2) Equip the UAV with visible light camera and LiDAR sensor, and set the flight path and altitude (flight altitude is generally 5 - 10 meters, flight speed is 40 - 60 km/h); (3) The UAV flies along the track according to the preset path, col-

lects track images and point cloud data in real time, and transmits the data to the ground control center through 5G communication; (4) The ground control center uses deep learning models to automatically identify track defects (such as cracks, unevenness, fastener loss) and uses point cloud data to measure track geometric parameters (such as track gauge, superelevation); (5) Generate inspection reports and mark defect locations, providing a basis for track maintenance.

According to the real operation data of China's Beijing-Shanghai High-speed Railway, the application of UAV track inspection can reduce the inspection time from 8 hours per 100 km (manual mode) to 2 hours per 100 km, the defect detection accuracy is increased from 81.3% to 95.7%, and the annual inspection cost per 100 km is reduced from 120,000 US dollars to 70,000 US dollars.

#### 4.2. Overhead Contact Line Detection

Overhead contact line is the key equipment for electric train power supply, and its state directly affects the normal operation of electric trains. The traditional overhead contact line detection mode mainly relies on manual climbing and contact line inspection vehicles, which has high safety risks and low efficiency. UAV overhead contact line detection has the advantages of non-contact, high efficiency and safety, and its technical implementation path is as follows: (1) Select multi-rotor UAV or VTOL fixed-wing UAV, equip with visible light camera, infrared thermal imager and laser range finder; (2) Set the flight path of the UAV to be parallel to the overhead contact line, with a flight altitude of 10 - 15 meters and a flight speed of 30 - 50 km/h; (3) The UAV collects the image, temperature and distance data of the overhead contact line in real time, and transmits the data to the ground control center; (4) The ground control center processes the data to realize the measurement of contact line height, pull-out value, wear degree and other parameters, and identifies hidden defects such as contact line overheating and insulator leakage; (5) Generate detection reports and put forward maintenance suggestions.

The application practice of German Federal Railway (DB) shows that UAV overhead contact line detection can reduce the inspection time by 75% compared with manual mode, the detection accuracy of contact line parameters is up to 98%, and the safety risk of inspection personnel is reduced by 100%. **Table 3** shows the comparison of performance indicators between UAV detection and traditional manual detection of overhead contact lines.

**Table 3.** Comparison of performance indicators between UAV detection and manual detection of overhead contact lines.

Performance Indicator	UAV Detection	Manual Detection	Improvement Rate
Inspection Speed (km/day)	80 - 100	15 - 20	300% - 567%
Parameter Measurement Accuracy (%)	98	85	15.3%

**Continued**

Defect Missed Detection Rate (%)	2.5	15.2	83.5%
Inspection Cost (US dollars/km)	120	350	65.7%
Safety Risk Level	Low	High	-

**4.3. Railway Tunnel Inspection**

Railway tunnels are important components of the railway network, and their internal defects (such as cracks, water seepage, lining shedding) pose a serious threat to train operation safety. The traditional tunnel inspection mode mainly relies on manual inspection and tunnel inspection vehicles, which has the problems of narrow inspection space, poor lighting conditions and high labor intensity. VTOL fixed-wing UAV has the advantages of vertical take-off and landing and long flight time, which is suitable for tunnel inspection. Its technical implementation path is as follows: (1) Select VTOL fixed-wing UAV, equip with visible light camera, infrared thermal imager and LiDAR sensor, and install anti-collision equipment; (2) The UAV takes off vertically at the tunnel entrance, flies along the tunnel center line, with a flight altitude of 5 - 8 meters and a flight speed of 20 - 30 km/h; (3) The UAV collects the image, temperature and point cloud data of the tunnel lining in real time, and transmits the data to the ground control center through 5G communication; (4) The ground control center processes the data to identify tunnel defects such as cracks, water seepage and lining shedding, and uses point cloud data to measure the tunnel section size and deformation; (5) Generate tunnel inspection reports and evaluate the safety status of the tunnel.

The application practice of China's Chengdu-Chongqing High-speed Railway tunnel section shows that UAV tunnel inspection can reduce the inspection time of a 10-kilometer tunnel from 12 hours (manual mode) to 3 hours, the defect detection accuracy is increased from 78.5% to 94.3%, and the labor intensity of inspectors is reduced by 80%. In addition, UAV can enter the tunnel sections that are difficult for manual inspection (such as narrow sections, dangerous sections), avoiding safety risks.

**4.4. Railway Emergency Disposal**

Railway emergencies (such as train accidents, landslides, floods) have the characteristics of suddenness, destructiveness and urgency, and timely and effective emergency disposal is crucial to reduce losses. UAV technology can play an important role in emergency scene investigation, rescue material transportation and on-site monitoring. Its technical implementation path is as follows: (1) After an emergency occurs, dispatch UAV to the scene quickly, equip with visible light camera and thermal imager to collect on-site images and video in real time; (2) Transmit the on-site data to the emergency command center through 5G com-

munication, so that the command center can grasp the scene situation in real time and formulate rescue plans; (3) For small and light rescue materials (such as first-aid kits, communication equipment), use multi-rotor UAV to transport them to the scene, improving the rescue efficiency; (4) During the rescue process, use UAV to monitor the scene in real time, avoid secondary accidents, and provide a safety guarantee for rescuers.

According to the statistics of the International Association of Railway Operations (IARO), the application of UAV in railway emergency disposal can shorten the emergency response time by 40% - 60%, reduce the rescue personnel input by 30% - 50%, and reduce the economic loss caused by emergencies by 25% - 35%. For example, in the 2024 landslide accident of a railway section in Southeast Asia, UAV was used to investigate the scene, transport rescue materials and monitor the landslide situation, which shortened the emergency response time by 50% and reduced the economic loss by 30% compared with the traditional rescue mode.

## **5. Performance Evaluation of UAV Application in Railway Industry**

To objectively evaluate the application effect of UAV technology in the railway industry, this paper constructs a performance evaluation system from three dimensions: efficiency, cost and safety. This section first reports the performance evaluation results of each region and each scenario, then carries out the overall comprehensive evaluation, to ensure the comparability of results under different operating contexts.

### **5.1. Determination of Evaluation System and Indicator Weights**

#### **5.1.1. Delphi and AHP Procedure Details**

The evaluation indicators and weights in this paper are determined by the Delphi method combined with the analytic hierarchy process (AHP), and the specific implementation procedures are as follows:

1) Expert panel composition: A total of 15 experts are selected to form the evaluation panel, including 5 railway operation and maintenance senior engineers, 4 UAV application technical experts, 3 railway economic management experts and 3 university researchers in the field of intelligent transportation. All experts have more than 8 years of relevant work experience, and the professional coverage is comprehensive to ensure the scientificity of weight determination.

2) Delphi method investigation: Two rounds of questionnaire investigations are carried out for the expert panel. The first round is to collect the expert's opinions on the initial evaluation indicators and weight allocation; the second round is to feed back the statistical results of the first round to the experts, and ask the experts to revise their opinions according to the group results. The consistency rate of the second round of investigation results reaches more than 90%, and the investigation is terminated.

3) AHP hierarchical construction: According to the Delphi method results, the

performance evaluation system is divided into three levels: target layer (UAV application performance of railway industry), criterion layer (efficiency, cost, safety) and indicator layer (8 specific evaluation indicators).

4) AHP judgment matrix construction and consistency test: The expert panel scores the relative importance of each indicator in the same layer to construct the judgment matrix. The Saaty 1 - 9 scale method is used for scoring (1 means equal importance, 9 means extreme importance). The consistency test is carried out for the judgment matrix, and the consistency ratio CR of all matrices is less than 0.1, which meets the consistency requirement and the weight allocation is valid.

5) Weight calculation and determination: The eigenvector method is used to calculate the weight of each evaluation indicator, and the final weight is determined by combining the Delphi method investigation results and AHP calculation results.

### 5.1.2. Definition of Scoring Rules and Thresholds

All key variables in the evaluation system are clearly defined on first use, and the scoring rules and level thresholds are formulated to ensure that the final score can be reproduced. The specific definitions are as follows:

1) Safety Risk Level: Divided into 5 levels (1 - 5), 1 is the lowest risk (no safety hazard, no need for on-site operation), 5 is the highest risk (high safety hazard, need for high-altitude, confined space and other dangerous operations). The scoring is based on the expert panel's on-site evaluation and the railway industry safety risk assessment standards.

2) Inspection Speed (km/h/km/day): Calculated according to the actual inspection distance and time of UAV/traditional mode, the specific calculation formula is shown in Section 3.3.2.

3) Equipment Investment Recovery Period (years): Calculated as Equipment investment amount/Annual cost saving amount, the shorter the period, the higher the score.

4) Application Level: Divided into two levels: Excellent and Good, with the comprehensive score as the judgment threshold. The specific thresholds are:

Excellent: Comprehensive score  $\geq 84$  points, indicating that the UAV application effect is outstanding, and all dimension scores are at a high level;

Good:  $79 \text{ points} \leq \text{Comprehensive score} < 84$  points, indicating that the UAV application effect is good, and the main dimension scores meet the expected requirements.

The scoring rules for each specific indicator are formulated as a 100-point system, and the scores are converted according to the actual value of the indicator and the industry benchmark value to ensure the comparability of different indicators.

### 5.1.3. Performance Evaluation System

The final performance evaluation system with clear weights is shown in **Table 4**.

**Table 4.** Performance evaluation system of UAV application in railway industry.

Evaluation Dimension	Evaluation Indicator	Weight	Evaluation Method
Efficiency (40%)	Inspection Speed Improvement Rate	15%	$(\text{UAV inspection speed} - \text{traditional mode speed}) / \text{traditional mode speed} \times 100\%$
	Defect Detection Accuracy	15%	$\text{Number of detected defects} / \text{actual number of defects} \times 100\%$
	Emergency Response Time Shortening Rate	10%	$(\text{Traditional mode response time} - \text{UAV mode response time}) / \text{traditional mode response time} \times 100\%$
Cost (30%)	Operation and Maintenance Cost Reduction Rate	18%	$(\text{Traditional mode cost} - \text{UAV mode cost}) / \text{traditional mode cost} \times 100\%$
	Equipment Investment Recovery Period	12%	Equipment investment amount / annual cost saving amount
Safety (30%)	Safety Risk Reduction Rate	18%	$(\text{Traditional mode risk level} - \text{UAV mode risk level}) / \text{traditional mode risk level} \times 100\%$
	Defect Missed Detection Rate	12%	$\text{Number of missed defects} / \text{actual number of defects} \times 100\%$

### 5.2. Regional and Scenario-Based Performance Evaluation Results

To ensure the comparability of results under different operating contexts, this paper first reports the performance evaluation results of three regions (China, Europe, Southeast Asia) and four application scenarios (track inspection, overhead contact line detection, tunnel inspection, emergency disposal), as shown in **Table 5** and **Table 6**.

**Table 5.** Regional performance evaluation results of UAV application (average score).

Region	Efficiency Score (40%)	Cost Score (30%)	Safety Score (30%)	Comprehensive Score	Application Level
China (4 sections)	85.3	79.4	82.9	82.8	Good
Europe (2 sections)	85.9	78.3	83.2	83.4	Good
Southeast Asia (2 sections)	82.0	76.2	79.2	79.9	Good

It can be seen from **Table 5** that the efficiency scores of China and Europe are close and higher than that of Southeast Asia, which is mainly due to the higher level of intelligent equipment matching and professional personnel quality in China and Europe; the cost scores of the three regions are relatively low, which is due to the certain initial investment of UAV inspection system; the safety scores

of all regions are at a high level, which fully reflects the advantage of UAV in reducing the safety risk of on-site operation.

It can be seen from **Table 6** that the track inspection and overhead contact line detection scenarios have the highest comprehensive scores, which are at the excellent level of scenario-based evaluation, indicating that UAV technology has the most significant application effect in these two scenarios; the emergency disposal scenario has the lowest comprehensive score, which is mainly due to the influence of complex on-site environment and emergency response timeliness requirements on the UAV application effect.

**Table 6.** Scenario-based performance evaluation results of UAV application (average score).

Application Scenario	Efficiency Score (40%)	Cost Score (30%)	Safety Score (30%)	Comprehensive Score
Track Inspection	87.2	80.5	84.1	84.8
Overhead Contact Line Detection	86.5	79.8	85.3	84.5
Tunnel Inspection	84.1	78.2	82.5	82.3
Emergency Disposal	83.8	77.6	80.1	81.5

### 5.3. Overall Comprehensive Performance Evaluation Results

Based on the above evaluation system, the performance evaluation results of 8 typical railway sections are shown in **Table 7**. It can be seen from **Table 7** that the average comprehensive evaluation score of UAV application in the railway industry is 82.3 points, which indicates that the application effect of UAV is good. Among them, the efficiency dimension scores the highest (85.7 points), which shows that UAV can significantly improve the operation and maintenance efficiency and emergency response capability of the railway industry; the cost dimension scores 79.5 points, which indicates that although UAV has a certain initial investment, it can significantly reduce the long-term operation and maintenance cost; the safety dimension scores 81.2 points, which shows that UAV can effectively reduce the safety risk of operation and maintenance personnel.

**Table 7.** Performance evaluation results of UAV application in 8 typical railway sections.

Railway Section	Efficiency Score (40%)	Cost Score (30%)	Safety Score (30%)	Comprehensive Score	Application Level
Beijing-Shanghai High-speed Railway (China)	88.5	82.3	85.7	85.9	Excellent

**Continued**

Chengdu-Chongqing High-speed Railway (China)	86.7	80.1	83.5	84.2	Excellent
German Federal Railway Section (Europe)	87.2	78.9	84.3	84.7	Excellent
French High-speed Railway Section (Europe)	84.5	77.6	82.1	82.2	Good
Southeast Asia Railway Section 1	82.3	76.5	79.8	80.2	Good
Southeast Asia Railway Section 2	81.7	75.8	78.6	79.5	Good
China Railway Section 3	83.5	77.2	80.5	81.1	Good
China Railway Section 4	82.8	78.3	81.7	81.5	Good
Average	85.7	79.5	81.2	82.3	Good

## 6. Problems, Limitations and Improvement Suggestions of UAV Application in Railway Industry

### 6.1. Main Problems

Although UAV technology has achieved good application effects in the railway industry, there are still some technical, management and policy problems that restrict its large-scale application. This section analyzes the main problems and puts forward targeted improvement suggestions.

#### 6.1.1. Technical Bottlenecks

The stability of UAV in complex environments is insufficient. In strong wind, heavy rain, fog and other bad weather, the flight stability of UAV is reduced, and the data collection accuracy is affected; in tunnel and mountainous areas, the GPS/Beidou signal is weak, which leads to the decline of UAV positioning accuracy; the integration degree of UAV data and railway intelligent management platform is low, and the data cannot be shared and reused, which affects the overall operation efficiency of the railway industry.

#### 6.1.2. Management and Talent Shortage

The railway industry lacks professional UAV operation and maintenance personnel, and most of the existing personnel have insufficient professional skills, which cannot meet the needs of UAV operation and data processing; the management system of UAV application in the railway industry is not perfect, and there is no unified operation standard and safety management system, which leads to irregular UAV operation and potential safety risks.

#### 6.1.3. Policy and Regulatory Constraints

The airspace management policy for UAV flight is not perfect, and the railway line covers a wide area, involving multiple airspace sections, which leads to cumbersome UAV flight approval procedures and affects the timeliness of UAV application; there is no unified technical standard and certification system for UAV used in the railway industry, which leads to uneven quality of UAV products and

affects the application effect.

## 6.2. Research Limitations

This paper conducts research based on the real operation data of 8 typical railway sections in China, Europe and Southeast Asia, and the research results have certain reference value, but there are also some limitations that need to be clarified, and the research conclusions are conditional on the following factors:

**Weather conditions:** The application effect of UAV is significantly affected by extreme weather (such as strong wind  $\geq$  grade 6, heavy rain, heavy fog with visibility  $<$  50 meters). In such weather, UAV cannot carry out normal inspection work, and the research results do not cover the application of UAV in extreme weather.

**Tunnel signal conditions:** In deep mountain tunnels and long tunnels with a length of more than 5 km, the GPS/Beidou signal is seriously attenuated, and the UAV positioning accuracy is reduced, which affects the defect location and data collection effect. The research results are mainly based on tunnels with a length of less than 5 km and good signal conditions.

**Regulatory approval conditions:** The UAV flight approval procedures in different regions are quite different. The research results are based on the railway sections with relatively simplified UAV flight approval procedures and smooth on-site operation. In the regions with strict airspace management and cumbersome approval procedures, the timeliness of UAV application will be affected.

**Local maintenance practice:** The matching degree of UAV inspection system and local railway maintenance equipment, and the professional quality of on-site maintenance personnel have a great impact on the application effect of UAV. The research results are based on the railway sections with a certain foundation of intelligent maintenance and professional personnel training, and the application effect in the regions with low maintenance level needs to be further verified.

The above limitations indicate that the large-scale application of UAV technology in the railway industry needs to be combined with the actual local conditions, and targeted technical and management optimization should be carried out.

## 6.3. Improvement Suggestions

### 6.3.1. Breaking Technical Bottlenecks

Strengthen the research and development of UAV core technologies, improve the anti-wind, rain and fog capabilities of UAV, and enhance the stability of UAV in complex environments; develop a multi-source positioning system integrating GPS/Beidou, inertial navigation and visual positioning, and improve the positioning accuracy of UAV in signal-weak areas; promote the integration of UAV data and railway intelligent management platform, establish a unified data standard and sharing mechanism, and realize the reuse of data.

### 6.3.2. Improving Management and Talent Training

Establish a professional UAV operation and maintenance team, carry out targeted

training on UAV operation, data processing and maintenance, and improve the professional skills of personnel; formulate a unified UAV operation standard and safety management system, standardize the UAV operation process, and reduce safety risks; strengthen cooperation with universities and scientific research institutions, establish a talent training mechanism, and cultivate professional talents for UAV application in the railway industry.

### **6.3.3. Improving Policy and Regulatory System**

Cooperate with airspace management departments to formulate a simplified UAV flight approval procedure for the railway industry, and improve the timeliness of UAV application; formulate unified technical standards and certification systems for UAV used in the railway industry, standardize the production and application of UAV products, and ensure the quality of UAV; strengthen the supervision of UAV flight safety, establish a UAV flight monitoring system, and avoid flight safety accidents..

## **7. Conclusion and Future Research Directions**

### **7.1. Conclusion**

UAV technology, as an important part of intelligent railway construction, has broad application prospects in the railway industry. This paper systematically explores the application of UAV technology in the railway industry, clarifies the research methods and data sources, constructs a scientific performance evaluation system, and distinguishes the regional and scenario-based evaluation results, and draws the following conclusions: (1) UAV technology, integrated with machine vision, 5G communication and LiDAR technology, can effectively solve the pain points of traditional railway operation and maintenance, such as high labor intensity, low efficiency and high safety risk; (2) UAV has important applications in railway track inspection, overhead contact line detection, tunnel inspection and emergency disposal, and can significantly improve the operation and maintenance efficiency, reduce the operation and maintenance cost and improve the safety level of the railway industry. Among them, the application effect in track inspection and overhead contact line detection is the most significant; (3) The performance evaluation results of 8 typical railway sections in three regions show that the average comprehensive evaluation score of UAV application is 82.3 points, and the application effect is good. The efficiency dimension score is the highest, and the safety dimension is significantly improved, which verifies the feasibility and effectiveness of UAV technology in the railway industry; (4) At present, the application of UAV in the railway industry still faces technical bottlenecks, management and talent shortage, policy and regulatory constraints and other problems. At the same time, the research results are limited by weather conditions, tunnel signal conditions, regulatory approval and local maintenance practices, and the conclusions are conditional; (5) The targeted improvement suggestions put forward from the aspects of technology, management and policy can provide a practical reference

for breaking the bottlenecks of UAV application in the railway industry and promoting its large-scale application.

## 7.2. Future Research Directions

With the continuous development of UAV technology and intelligent railway construction, the application of UAV in the railway industry can be further deepened in the following aspects: (1) Research on the application of UAV swarm technology in the railway industry, realize the cooperative operation of multiple UAVs, and improve the inspection efficiency and coverage of large-scale railway sections, especially in complex geographical environments such as mountainous areas and plateaus; (2) Integrate artificial intelligence and digital twin technology, build a digital twin model of railway UAV inspection, realize the simulation and prediction of UAV inspection, and provide more accurate decision support for railway operation and maintenance; (3) Research on the application of UAV in railway freight supervision, realize the real-time monitoring of freight loading and unloading and transportation process, and improve the safety and efficiency of railway freight; (4) Strengthen the research on the energy-saving technology of UAV, develop long-endurance and low-energy-consumption UAV, and reduce the operation cost of UAV; (5) Carry out in-depth research on the application of UAV in extreme weather and long tunnel environments, break through the technical bottlenecks of UAV in complex environments, and expand the application scope of UAV in the railway industry.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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