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POLICE SPORTS REHABILITATION TECHNOLOGY UTILIZING MULTI-SENSOR DATA

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Abstract: As the complexity and hazards associated with police work continue to escalate, law enforcement officers are increasingly susceptible to physical injuries. This study investigates the application of police sports rehabilitation technology that utilizes multi-sensor data, with the objective of acquiring comprehensive and precise rehabilitation information through the integration of multi-sensor data. The research aims to facilitate accurate analysis and the development of tailored rehabilitation programs by employing advanced algorithms. This article delineates the critical importance of multi-sensor data in the context of police sports rehabilitation, encompassing the monitoring of motion postures and the assessment of physiological parameters. Furthermore, it delves into the methodologies and technologies pertinent to multi-sensor data fusion, as well as strategies for customizing and optimizing rehabilitation programs based on data-driven approaches. The findings of this study provide substantial support for the physical rehabilitation of police officers and their reintegration into the workforce, underscoring its significant practical implications and application value.
Keywords: Multi-sensor data; Police sports rehabilitation; Data fusion; Rehabilitation program optimization

1 INTRODUCTION

In the context of social transformation and an increasingly complex security landscape, law enforcement agencies are encountering unprecedented challenges. The emergence of new forms of criminal activity, characterized by heightened intelligence and violence, necessitates that police officers engage in a range of critical tasks, including counter-terrorism, emergency response, and public safety patrols [1]. These responsibilities demand not only exceptional physical fitness but also the ability to navigate various sudden and hazardous situations. Injuries sustained by officers can severely impact their individual health and significantly disrupt the normal functioning of police operations, often resulting in prolonged absences that diminish the overall efficacy of social security prevention and control measures.
Traditional approaches to police sports rehabilitation predominantly rely on manual assessments conducted by rehabilitation therapists, alongside empirical rehabilitation strategies. In practice, therapists frequently evaluate the physical condition of injured officers through visual observation, rudimentary physical examinations, and subjective inquiries. For instance, joint mobility assessments typically involve manual measurements using protractors, a method that is cumbersome and susceptible to considerable measurement errors, thereby complicating the accurate detection of subtle changes in joint movement during dynamic activities. Furthermore, when developing rehabilitation plans, individual factors such as the officer's age, physical condition, injury location, and severity are often inadequately addressed, leading to inconsistent rehabilitation outcomes. More critically, conventional rehabilitation models lack real-time dynamic monitoring and feedback mechanisms [2], which precludes timely adjustments to rehabilitation strategies based on the evolving physical condition of the officer during recovery. This can result in excessively prolonged rehabilitation periods, suboptimal recovery outcomes, and the potential for secondary injuries.
The rapid advancement of sensor technology, data processing capabilities, and artificial intelligence algorithms presents significant opportunities for enhancing medical rehabilitation through the application of multi-sensor data. Various sensors, including accelerometers, gyroscopes, heart rate monitors, and electromyography sensors, can accurately and in real-time collect multidimensional data regarding human movement, physiological parameters, and muscle activity throughout the rehabilitation process. By utilizing sophisticated data fusion and analysis techniques, these heterogeneous data sources can be integrated and processed, facilitating a comprehensive exploration of the underlying information. This approach provides an objective, scientific, and thorough foundation for the formulation and adjustment of rehabilitation plans. The integration of multi-sensor data technology into police sports rehabilitation is anticipated to overcome the limitations of traditional rehabilitation methods, addressing the personalized and efficient rehabilitation needs of police officers and aiding injured personnel in swiftly restoring their physical capabilities and resuming their duties. This advancement holds significant implications for enhancing the operational effectiveness of law enforcement agencies and ensuring the stability of social security.

2 CURRENT RESEARCH OF POLICE SPORTS REHABILITATION TECHNOLOGY

The understanding of human movement rehabilitation is a fundamental aspect of motion analysis and assessment research, which is crucial for informing patient rehabilitation training and fostering a healthy lifestyle. The advent of machine learning technologies and advancements in computational capabilities have facilitated the development of compact and user-friendly portable sensors, significantly improving the training efficiency for patients with limb disabilities. For instance, researchers such as Panwar [3] have employed wearable sensors to gather data that effectively categorizes rehabilitation movements in the arms of stroke patients. Similarly, the Mario team [4] utilized pressure sensors embedded in insoles to monitor pressure distribution across various regions of the foot during ambulation, thereby analyzing the gait characteristics of stroke patients. Furthermore, the mirror therapy enabler, a robotic apparatus designed to assist patients with upper limb dysfunction in their exercises, employs a 6-axis inertial force sensor to accurately measure the force and torque exerted between the affected and unaffected limbs during rehabilitation, thereby enhancing the precision of rehabilitation training [5]. Video image processing technology has demonstrated considerable potential in the analysis of human motion perception, with applications spanning clinical diagnosis, rehabilitation treatment, and sports science. In particular, within the medical domain, this technology aids healthcare professionals in analyzing motion data from patients with limb dysfunction, significantly benefiting disease diagnosis and monitoring rehabilitation progress [6]. The Matos team employed stereo cameras to track the movement trajectories of patients in rehabilitation settings, utilizing this data to assess the effectiveness of training interventions [7]. Electromyography (EMG), which captures the bioelectric signals associated with muscle activity through electrodes, offers an objective and quantitative approach for assessing muscle function. Wei et al. [8] have utilized high-density surface electromyography (sEMG) in conjunction with pattern recognition technology to establish a rehabilitation environment that enables real-time classification of forearm rehabilitation movements, thereby facilitating the enhancement of fine motor skills in the forearm.

3 ANALYSIS OF THE DEMAND FOR POLICE SPORTS REHABILITATION TECHNOLOGY

3.1 Characteristics of Police Sports Rehabilitation Needs

Traditional approaches to police sports rehabilitation predominantly depend on manual evaluations conducted by rehabilitation therapists, alongside empirical rehabilitation strategies. Therapists typically assess the physical condition of injured personnel through observational techniques and basic physical examinations, which are inherently subjective and hinder the acquisition of comprehensive and precise rehabilitation data. For instance, when assessing joint range of motion, reliance on visual observation and manual measurements can result in considerable inaccuracies, failing to capture subtle variations in joint movement. Furthermore, the formulation of rehabilitation plans often employs standardized rehabilitation protocols and training regimens, which inadequately account for individual differences, leading to inconsistent rehabilitation outcomes. Additionally, conventional rehabilitation processes lack mechanisms for real-time monitoring and dynamic adjustments regarding rehabilitation efficacy, thereby precluding timely optimization of rehabilitation plans based on the actual recovery trajectories of the injured individuals.

Consequently, the police force exhibits distinct requirements in the realm of sports rehabilitation. Firstly, the physical fitness standards requisite for police work are exceptionally high, encompassing strength, endurance, speed, agility, and coordination. Therefore, the objective of rehabilitation extends beyond mere restoration of physical function; it also aims to facilitate a swift return to a physical state that enables police officers to perform high-intensity law enforcement duties. Secondly, the exigent nature of police work necessitates a reduction in the rehabilitation cycle to the greatest extent possible, thereby minimizing the impact of injury-related absences on law enforcement operations. Moreover, given the complex and varied nature of injuries sustained by police officers in the line of duty, rehabilitation plans must be highly individualized and targeted.

3.2 The Necessity of Introducing Multi-Sensor Data

The integration of multi-sensor data represents a viable solution to the shortcomings of traditional police sports rehabilitation technology. By employing a range of sensors, including accelerometers, gyroscopes, heart rate monitors, and electromyography sensors, it becomes feasible to gather real-time and precise multidimensional data regarding the injured individual's movement patterns, joint angles, muscle activity, heart rate, blood pressure, and other relevant metrics throughout the rehabilitation process. This data can provide a comprehensive and objective representation of the physical condition and rehabilitation progress of the injured, thereby establishing a robust data foundation for therapists to devise personalized and precise rehabilitation plans. Concurrently, a real-time monitoring system predicated on multi -sensor data can swiftly detect any irregularities during the rehabilitation process, facilitating dynamic adjustments to the rehabilitation plan. This approach significantly enhances rehabilitation effectiveness and efficiency, thereby addressing the specialized sports rehabilitation needs of the police force.

4 THE INTEGRAL ROLE OF MULTI-SENSOR DATA IN POLICE SPORTS REHABILITATION

4.1 Monitoring and Analyzing Movement Posture

In the context of police sports rehabilitation, the precise monitoring of the movement posture of injured personnel is essential for evaluating the effectiveness of rehabilitation efforts and mitigating the risk of secondary injuries. The utilization of accelerometers and gyroscopes facilitates the real-time measurement of acceleration and angular velocity across various body segments. Through the application of data fusion algorithms, these devices can accurately compute joint movement angles and trajectories. For instance, during lower limb rehabilitation exercises, sensors can be affixed to the thigh, calf, and foot to track the flexion and extension angles, as well as the range of motion of the knee and ankle joints during activities such as ambulation and running. This data enables rehabilitation therapists to assess the normalcy of the injured individual's gait and identify any restrictions in joint mobility or abnormal compensatory movements. Should an excessive inward rotation of the knee joint be observed during ambulation, the therapist can promptly modify the rehabilitation regimen, intensifying targeted muscle strength and joint stability training to rectify the abnormal gait and facilitate the rehabilitation process.

4.2 Assessment and Monitoring of Physiological Parameters

Physiological parameters serve as critical indicators of bodily functions and the rehabilitation status of injured individuals. Real-time monitoring of heart rate, blood pressure, and blood oxygen saturation can be achieved through the use of heart rate sensors, blood pressure monitors, and blood oxygen saturation sensors during rehabilitation training. This information aids therapists in gauging the injured person's tolerance to rehabilitation activities, thereby preventing injuries associated with overexertion. For example, during aerobic rehabilitation exercises, monitoring heart rate allows therapists to maintain it within an appropriate training range, tailored to the individual's age, physical condition, and stage of rehabilitation. An elevated heart rate may signal excessive training intensity, warranting a reduction in exercise intensity or an extension of rest periods; conversely, a low heart rate may indicate insufficient training intensity to achieve the desired rehabilitation outcomes. Furthermore, ongoing monitoring of blood pressure and blood oxygen saturation can facilitate the timely identification of potential cardiovascular complications or respiratory dysfunctions, thereby ensuring the safety of the rehabilitation process.

4.3 Monitoring Muscle Function and Rehabilitation Guidance

Electromyography (EMG) sensors are employed to capture the electrical signals produced by muscles during contraction and relaxation. Analyzing these signals allows for the assessment of muscle functional status and fatigue levels. In police sports rehabilitation, EMG sensors are particularly valuable for individuals experiencing impaired muscle function due to strains, sprains, or nerve injuries. Therapists can monitor the EMG signals of injured individuals during muscle strength training to evaluate muscle activation levels and recruitment patterns. A muscle exhibiting weak EMG signals during training may indicate inadequate muscle strength, necessitating an increase in targeted training intensity and methodologies. Additionally, continuous monitoring of EMG signal variations over time enables therapists to evaluate the recovery of muscle function, thereby informing adjustments to rehabilitation plans. For example, in hand muscle rehabilitation, the attachment of EMG sensors to the hand muscle groups allows therapists to monitor the real-time activity of the finger flexor and extensor muscles, guiding the injured individual in precise rehabilitation exercises aimed at enhancing the strength and coordination of hand muscles, ultimately promoting the recovery of hand function.

5 MULTI-SENSOR DATA FUSION TECHNOLOGY AND METHODS

5.1 Principles and Significance of Multi-Sensor Data Fusion

Multi-sensor data fusion encompasses the systematic integration of diverse data types obtained from multiple sensors to yield more precise and holistic information. In the context of police sports rehabilitation, the data gathered from various sensors exhibit both complementary and redundant characteristics. For instance, while accelerometers and gyroscopes can provide insights into motion posture, they lack the capability to monitor physiological parameters. Conversely, heart rate and blood pressure sensors are primarily designed to track physiological metrics and do not capture motion posture data. Through the process of data fusion, these complementary datasets can be amalgamated, thereby reducing redundancy and enhancing the reliability and accuracy of the information. Furthermore, data fusion facilitates a multidimensional analysis of an injured individual's physical condition, thereby providing a more robust and scientific foundation for the development and modification of rehabilitation plans, ultimately improving the effectiveness and efficiency of rehabilitation efforts.

5.2 Common Methods of Multi-Sensor Data Fusion

5.2.1 Weighted Average Method

The weighted average method represents a straightforward and intuitive approach to data fusion. This technique involves assigning a weight to each sensor's data based on the reliability and significance of the information provided by different sensors, followed by averaging the weighted sensor data to derive the fusion outcome. For example, when integrating acceleration data from multiple accelerometers monitoring the same object, a sensor exhibiting higher accuracy and stability would receive a larger weight, while sensors with lower accuracy and greater susceptibility to interference would be assigned smaller weights. Although the weighted average method is relatively easy to implement and compute, the determination of weights can be somewhat subjective and may not adequately account for the interdependencies among sensor data.

5.2.2 Neural Network Fusion Method

The neural network fusion method leverages the advanced nonlinear mapping and data processing capabilities inherent in artificial neural networks to facilitate the fusion of multi-sensor data. Initially, data collected from various sensors serve as inputs to the neural network, which is trained to discern the intrinsic relationships and patterns among the data from different sensors. In practical applications, when new sensor data is introduced, the neural network can generate a fused output based on the knowledge acquired during training. This method exhibits considerable adaptability and is adept at managing complex nonlinear relationships. For instance, when integrating motion posture data with physiological parameter data, the intricate nonlinear relationship between these two types of data poses challenges for traditional fusion methods. The neural network fusion method, however, can autonomously learn the correlations between variations in motion posture and corresponding physiological responses through extensive training data, thereby achieving more accurate data fusion and providing comprehensive and precise information for rehabilitation assessment.

5.3 Application Process of Multi-Sensor Data Fusion in Police Sports Rehabilitation

5.3.1 Constructing a Motion State Detection Algorithm Based on Limb Situation Awareness

The initial step involves defining the limb motion states to be detected, such as running, jumping, and walking, along with their associated key features, which include position, speed, acceleration, and angle of the limbs. Motion data are collected through sensors (e.g., accelerometers, gyroscopes, magnetometers) or cameras. Subsequently, the collected data undergo cleaning, denoising, and smoothing processes to eliminate outliers and noise, thereby enhancing data accuracy and reliability. Relevant features pertaining to limb motion states are extracted from the preprocessed data. The model is then trained using known motion state data, enabling it to learn the characteristics and patterns associated with different motion states. Finally, the model's accuracy and reliability are validated by comparing its predictions with actual conditions. Should the model's performance be suboptimal, adjustments to model parameters or a reevaluation of training features may be warranted.

5.3.2 Designing Circuitry to Match the Detection Algorithm

The first step in this process involves amplifying the weak signals produced by the sensors to ensure accurate processing by subsequent circuits. Appropriate amplification factors and circuit topologies must be selected to prevent signal distortion. Following this, low-pass, high-pass, or band-pass filters are designed to eliminate noise and interference from the sensor output signals. The analog signals are then converted into digital signals for processing by subsequent digital signal processing algorithms, necessitating the selection of an analog-to-digital converter (ADC) chip characterized by high resolution and low noise. A microcontroller unit (MCU) with adequate processing capabilities and low power consumption is chosen to manage the digital signals output by the sensors, ensuring it can execute complex algorithms such as posture calculation, filtering, and feature extraction. Finally, the actual circuitry is constructed, followed by hardware debugging and testing to confirm that the circuit's functionality and performance meet established requirements, including sensor sensitivity, signal stability, and data accuracy.

5.3.3 Designing a Human-Machine Interaction System

The design of a human-machine interaction system predicated on limb situation awareness is a multifaceted yet promising endeavor that synthesizes knowledge from various domains, including human posture recognition technology, machine learning, and artificial intelligence. The primary objective of this system is to facilitate intelligent interaction with machines by recognizing and interpreting human posture information. This system is capable of capturing and analyzing data regarding the positions, angles, and movements of critical body parts, such as bones and joints, to discern user intentions and respond appropriately. Suitable communication protocols (e.g., Wi-Fi, Bluetooth) should be selected to enable data transmission and interaction between devices, leveraging cloud services for data storage, analysis, and sharing, as well as facilitating cross-device interaction. Interaction logic should be thoughtfully designed based on application scenarios and user requirements, ensuring that it is straightforward, intuitive, and user-friendly. The user interface should be developed in accordance with ergonomic and psychological principles to enhance the overall user experience.

6 DEVELOPMENT AND OPTIMIZATION OF POLICE SPORTS REHABILITATION PROGRAMS

6.1 Framework and Rationale for Rehabilitation Program Development

The formulation of police sports rehabilitation programs informed by multi-sensor data constitutes a methodical and empirical approach. Initially, rehabilitation therapists gather comprehensive physical data pertaining to the injured individual during the acute phase of injury, employing various sensors to capture information regarding motor function deficits, baseline physiological metrics, muscle strength, and joint mobility. Concurrently, a thorough analysis of this data is conducted in relation to the individual's occupational profile, the etiology of the injury, and the rehabilitation objectives. For instance, in the case of an individual with a leg fracture resulting from a capture operation, the therapist must prioritize factors such as the healing of the fractured bones, the restoration of lower limb muscle strength, and the re-establishment of gait patterns. Drawing upon the analytical findings, the therapist utilizes the insights derived from the multi-sensor data to devise a tailored rehabilitation program. This program encompasses the delineation of rehabilitation training phases, the specific training content and intensity for each phase, the selection of appropriate rehabilitation assistive devices, and the scheduling of rehabilitation sessions. Throughout the program's development, multi-sensor data serves as an objective and precise foundation for the therapist, facilitating the alignment of the program with the unique needs of the injured individual and enhancing rehabilitation outcomes.

6.2 Data-Driven Optimization Approaches for Rehabilitation Programs

Throughout the rehabilitation process, the individual's physical condition and progress are subject to dynamic changes, necessitating real-time adjustments to the rehabilitation program based on the monitoring results derived from multi-sensor data. Therapists continuously gather data regarding the individual's movement patterns, physiological parameters, and muscle function during rehabilitation sessions, employing data analysis algorithms for real-time evaluation. Should the training outcomes during a specific rehabilitation phase fall short of expectations—such as a sluggish improvement in joint mobility or minimal gains in muscle strength—the therapist can ascertain the underlying causes through data analysis, which may include inadequate training intensity, inappropriate training methodologies, or unsuitable rehabilitation assistive devices. Subsequently, the therapist implements targeted modifications to the rehabilitation program informed by the insights provided by the multi-sensor data. For example, adjustments may involve increasing training intensity, altering training techniques, or substituting with more appropriate rehabilitation assistive devices. This data-driven optimization strategy ensures that the rehabilitation program remains consistently aligned with the individual's actual rehabilitation status, thereby maximizing rehabilitation efficacy and reducing the duration of the rehabilitation process.

6.3 Case Study: Impact of Multi-Sensor Data-Driven Rehabilitation Programs

As an illustrative example, consider a police officer who incurred a knee injury while on duty and subsequently underwent sports rehabilitation treatment guided by multi-sensor data. In the initial stages of rehabilitation, data regarding the knee joint's movement patterns and muscle activity were collected using accelerometers, gyroscopes, and electromyography sensors, while physiological parameters were monitored through heart rate and blood pressure sensors. The therapist crafted a personalized rehabilitation program based on this data, which included initial interventions for knee joint immobilization and edema reduction, followed by mid-term training focused on joint mobility and muscle strength, and concluding with functional training. During the rehabilitation process, real-time monitoring of multi-sensor data indicated a slow increase in quadriceps strength during the mid-term muscle strength training phase. Further analysis of the electromyography data revealed deficiencies in the muscle activation pattern during quadriceps training. Consequently, the therapist modified the training methods based on the analytical results, incorporating targeted muscle activation exercises and appropriately increasing training intensity. Following a period of adjustment, subsequent monitoring of multi-sensor data demonstrated a significant enhancement in quadriceps strength, alongside marked improvements in knee joint stability and functional movement. Ultimately, the individual successfully regained knee function in a relatively brief timeframe and was able to resume police duties. This case exemplifies the capacity of sports rehabilitation programs informed by multi-sensor data to deliver precise rehabilitation interventions, thereby effectively improving rehabilitation outcomes and efficiency.

7 CONCLUSION

This study investigates the application of police sports rehabilitation technology utilizing multi-sensor data. It emphasizes the critical role of multi-sensor data in the rehabilitation of police personnel, exploring the technologies and methodologies for data fusion, as well as the development and optimization of rehabilitation plans informed by this data. The findings indicate that multi-sensor data can effectively and accurately monitor various parameters, including movement posture, physiological metrics, and muscle functionality throughout the rehabilitation process. This comprehensive monitoring provides a scientific foundation for the formulation and modification of rehabilitation strategies. Furthermore, the integration of multi-sensor data fusion technology enhances the reliability and precision of the data by leveraging the strengths of diverse sensors. Rehabilitation plans that are informed by multi-sensor data facilitate personalized and targeted treatment, thereby significantly improving rehabilitation outcomes and efficiency. Experimental results corroborate the efficacy and advantages of this technology in the context of police sports rehabilitation. The implementation of multi-sensor data-based rehabilitation technology holds considerable potential value and significance. From the perspective of individual police officers, this technology can expedite the recovery of injured personnel, thereby reducing absenteeism and mitigating the adverse effects of occupational injuries on their careers and overall quality of life. From an organizational standpoint, officers who recover swiftly can return to duty promptly, ensuring the continuity and effectiveness of police operations and enhancing public safety capabilities. Additionally, the adoption of this technology may foster innovation and advancement in the realm of police medical rehabilitation, offering valuable insights for research in sports rehabilitation across related fields.

Future research endeavors may concentrate on several key areas: Firstly, there is a need to further refine multi-sensor data fusion algorithms to enhance the accuracy and efficiency of data integration, particularly in managing complex and variable rehabilitation data. Secondly, in-depth investigations into rehabilitation prediction models utilizing big data and artificial intelligence should be conducted, analyzing extensive rehabilitation case data to forecast the recovery trajectories of injured individuals and identify potential complications, thereby providing a more robust scientific basis for the proactive adjustment of rehabilitation plans.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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THE INFLUENCE OF ELECTRIC HEATING CATALYST PLACEMENT ON THE AFTER-TREATMENT PERFORMANCE OF HEAVY-DUTY DIESEL VEHICLES

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Abstract: Based on a real driving emission test conducted on a heavy-duty diesel truck equipped with PEMS equipment under cold start and low-load conditions, this study investigates the influence of the EHC (electric heating catalyst) placement on the exhaust temperature, NO_x conversion efficiency, and EHC power consumption of the heavy-duty diesel vehicle's after-treatment system. The two after-treatment schemes tested are EHC+DOCoF+SCR+ASC (Scheme 1) and DOCoF+EHC+SCR+ASC (Scheme 2). The research findings indicate that, in Scheme 1, the temperatures at T4 (at the front end of the after-treatment system), T5 (after the DOCoF), and T6 (before the SCR) are higher than those in Scheme 2 during both cold start and low-load conditions. During the cold start phase, Scheme 1 excels in terms of urea injection timing, NO_x conversion efficiency, and EHC power consumption compared to Scheme 2. In the low-load phase, Scheme 1 outperforms Scheme 2 in terms of EHC power consumption, while its NO_x conversion efficiency is comparable to that of Scheme 2.
Keywords: Heavy-duty diesel vehicle; Electric heating catalyst; Real driving emission; Layout position; After-treatment

1 INTRODUCTION

With the rapid growth of China's economy and the continuous improvement of people's living standards, the number of cars in our country has been increasing year by year. In 2023, China's auto production and sales reached 30.11 million and 30.09 million units respectively, ranking first in the world for many consecutive years. The rapid growth of car ownership is accompanied by an increase in vehicle pollutant emissions, according to the "Annual Report on Mobile Source Environmental Management in China (2023)"released by the Ministry of Ecology and Environment[1]. In 2022, the national emissions of motor vehicle pollutants, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM), were 7.43 million tons, 1.912 million tons, 5.267 million tons, and 53,000 tons respectively. Among them, the NO_x emissions from heavy-duty diesel vehicles accounted for 78.3% of the total vehicle emissions. Reducing NO_x emissions from heavy-duty diesel vehicles has become the focus of research. Selective Catalytic reduction (SCR) technology, as an effective means to reduce NO_x emissions [2], has been widely applied in the after-treatment systems of heavy-duty diesel vehicles.

In low temperature environment, the efficiency of SCR system will be significantly affected, resulting in the increase of NO_x emissions. To solve the problem of low SCR conversion efficiency under low temperature and low load，Han Feng using the two-stage urea SCR system[3], the first stage SCR system is tightly coupled after the engine turbocharger. In the engine WHTC cycle, the SCR injection temperature is reached within 80s after cold start, about 450s earlier than that of the single-stage urea SCR system. Zhu Minlin adopting the dual-spray SCR system[4], NO_x emissions were significantly reduced compared to single-spray systems. The NO_x emissions in the cold-state WHTC cycle decreased by 65.4%, and those in the hot-state WHTC cycle decreased by 92.9%. Liu Chenxi studied the scheme of ozone collaborative treatment of NO_x under the cold start condition[5]. The test showed that ozone (O3) collaborative treatment could significantly reduce NO_x emissions at the cold start stage when the exhaust temperature was below 100 ℃, and the maximum conversion efficiency could reach 60.29%. Hasan's research has found that advancing or delaying the closing of the valves can increase the exhaust temperature of diesel engine after-treatment under low-load conditions[6], achieving an exhaust temperature increase of up to 60°C at most. Xie Yuzhuo found that the electric heating system can improve the aftertreatment temperature of diesel engines[7], thereby enhancing the conversion efficiency of SCR under cold start conditions. The higher the power of the electric heating system, the better the NO_x emission reduction effect. Leahey[8], Zamir[9], Manuel[10], Gao studied the NO_x emission reduction effect of electric heating system[11]. The experimental results show that exhaust electric heating is an effective technology that can reduce NO_x emissions during cold start of diesel vehicles.

In summary, both domestic and foreign researchers have carried out a great deal of research work in the field of aftertreatment technology for heavy-duty diesel vehicles, and corresponding research achievements have been obtained. Li Changyu[12], Ramadhas found that the transient emissions and specific emissions of NO_x under cold start conditions of diesel vehicles account for a relatively large proportion of the total emissions[13]. Zhang Dan and Wang have found that both transient and specific emissions of NO_x in low-speed and low-load cycles of diesel vehicles are very high[14,15], which requires special attention. Therefore, how to effectively reduce NO_x emissions from heavy-duty diesel vehicles during cold start and low-load conditions has become a key focus of current research. Among various research solutions, electric heating technology is a scheme that can effectively increase the exhaust temperature during cold start and low-load conditions without significantly affecting fuel consumption. In current studies, the electric heating arrangement is always positioned before the DOC, while there are few studies on placing the electric heating before the SCR system. Therefore, this paper uses a heavy-duty diesel vehicle equipped with an electric heating after-treatment system to carry out vehicle real-road emission tests under cold start and low-load conditions, aiming to investigate the influence of the electric heating arrangement position on the after-treatment performance of heavy-duty diesel vehicles during cold start and low-load conditions.

2 EXPERIMENTAL DESIGN

2.1 Test Vehicle and After-treatment System

The test vehicle is a stake diesel truck meeting the National VI emission standards. The main information of the vehicle is shown in Table 1 below.

Table 1 Vehicle and Engine Parameters

Parameters / Unit	Data
Engine Arrangement Form	In-line, front-engine rear-wheel drive
Intake Method	Turbocharging
Displacement/ L	2.5
Cylinder Number	4
Rated Power of Engine/ kW	100
Maximum Torque of Engine/ N·m	360
Rated Power Speed/ r·min-1	3200
curb Mass/ kg	2565
Maximum Mass/ kg	4495
Vehicle Dimensions/ mm	5990*2180*2391

The after-treatment system of the vehicle adopts a combination of EHC, DOCoF, SCR, and ASC. EHC (Electric Heating Catalyst) converts electrical energy into thermal energy through electric heating elements. When exhaust gas flows through the heating chamber, it is heated to the required temperature by the electric heating catalyst, The electric heating power is 1.5 kW and the power supply voltage is 12V. DOCoF (DOC on DPF) is a novel integrated after-treatment package combining DOC and DPF. Unlike the traditional separate packaging of DOC and DPF, the DOCoF integrates both functions into a shorter structure, enhancing exhaust heat preservation. It oxidizes CO, HC, and NO in the exhaust, raises exhaust temperature, traps particulate matter, and reduces PN and PM emissions. SCR (Selective Catalytic Reduction System) primarily reduces NOx in the exhaust. After the exhaust temperature reaches the urea injection threshold, the urea injection system sprays urea into the exhaust pipe. Under high temperatures, urea decomposes into ammonia (NH_3), which reacts with NO_x on the catalyst surface to convert NO_x into N_2 and H_2O. ASC (Ammonia Slip Catalyst) further oxidizes excessive or unreacted ammonia (NH_3) from the SCR system into harmless N_2 and H_2O, preventing ammonia from being directly released into the atmosphere.

2.2 Test Equipment

The test equipment is the OBS-ONE series portable emission testing system (PEMS) from Japanese brand HORIBA. This equipment can continuously measure the exhaust flow and emission pollutant concentrations of the test vehicle on actual roads, including NO_x, CO, CO_2, PN, etc. Meanwhile, it can real-time monitor the test environment temperature and humidity, GPS data and the vehicle's OBD information. By collecting the emission pollutant concentrations and exhaust flow, the emission mass of each exhaust pollutant can be calculated. Combined with the collected OBD parameters of the test vehicle, the specific emission of the vehicle can be determined.

2.2 Test Scheme

The test prototype shall not carry additional loads except for the testing equipment, equipment tooling, driver, and data collection engineer. The vehicle shall start the test with a cold start, and the water temperature of the prototype shall be less than 30°C before the test begins. The test shall be conducted on paved roads under low-load conditions, with the average vehicle speed ranging from 15 km/h to 20 km/h. The test duration shall be at least sufficient to ensure that the cumulative work of the test vehicle reaches 1 times the engine WHTC cycle work.The electric heating catalyst is based on the T6 temperature sensor: the electric heating system is activated when the T6 temperature is lower than 180°C and turned off when the T6 temperature exceeds 200°C. The test prototype shall carry out real-road emission tests with two after-treatment schemes respectively.

(1) After-treatment Scheme 1: EHC + DOCoF + SCR + ASC, as shown in Figure 1:

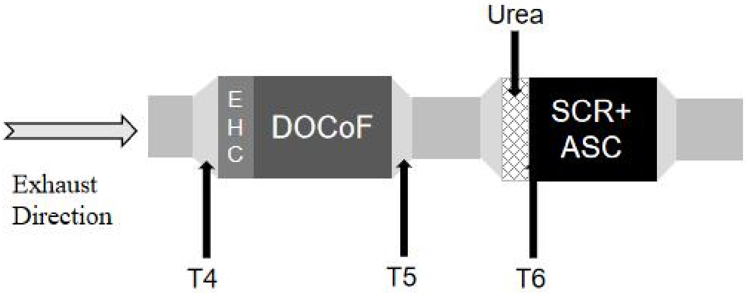

Figure 1 After-treatment Scheme 1

In this scheme, the electric heating catalyst is positioned at the front of the DOC in the after-treatment system. By heating the exhaust gas ahead of the DOC, the DOC can reach its oxidation temperature more rapidly. Once the DOC reaches the oxidation temperature, it releases heat through oxidation reactions. The thermal energy from both the oxidation reactions and electric heating diffuses to the downstream of the after-treatment system, increasing the temperature of the SCR system. NO_x will undergo a reduction reaction on the surface of the SCR catalyst, reducing NO_x emissions.

(2) After-treatment Scheme 2: DOCoF+EHC+SCR+ASC, as shown in Figure 2:

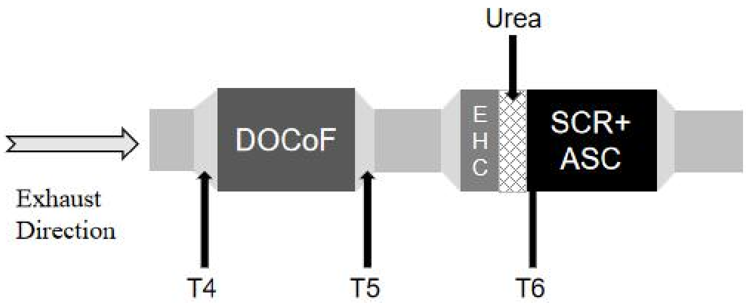

Figure 2 After-treatment Scheme 2

In this scheme, the electric heating catalyst is positioned in front of the SCR, which can directly heat the SCR system to increase its temperature. NO_x will undergo a reduction reaction on the surface of the SCR catalyst, reducing NO_x emissions.

3 RESULT AND DISCUSSION

3.1 Exhaust Temperature Characteristics During Cold Start

At the start of the test, the engine coolant temperature was below 30°C. The period from the start of the test until the engine coolant temperature reached 70°C is defined as the cold start phase. The cold start duration for Scheme 1 was 986 seconds, while that for Scheme 2 was 969 seconds. The exhaust gas temperatures at different positions in the after-treatment system were measured using temperature sensors T4, T5, and T6. Specifically, sensor T4 was located at the foremost end of the after-treatment system, sensor T5 at the rear end of the DOCoF, and sensor T6 at the front end of the SCR.

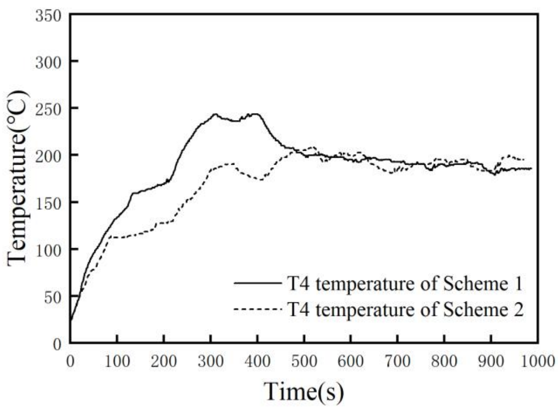

Figure 3 T4 Temperature during Cold Start

The figure 3 shows a comparison of T4 temperatures between the two schemes. The average temperature of Scheme 1 is 186.8°C, while that of Scheme 2 is 168.1°C. Since the EHC of Scheme 1 is located behind the T4 sensor, at the beginning of the test, both the engine exhaust temperature and the thermal radiation from the activated EHC act on T4, so the T4 temperature of Scheme 1 rises faster than that of Scheme 2. The EHC of Scheme 1 is turned off at 402 seconds, and the T4 temperature drops rapidly due to the absence of thermal radiation from the EHC. The EHC of Scheme 2 is turned off at 506 seconds. Since the EHC of this scheme is located in front of the SCR, the switching of the EHC has no effect on the T4 temperature. Subsequently, due to the similar driving conditions, the T4 temperatures of the two schemes gradually stabilize and remain between 180 and 210°C.

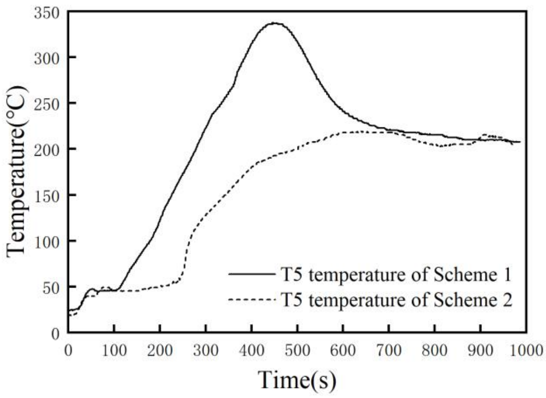

Figure 4 T5 Temperature during Cold Start

The figure 4 shows a comparison of T5 temperatures between the two schemes. The average temperature of Scheme 1 is 203.1°C, while that of Scheme 2 is 155.1°C. The T5 temperature of Scheme 1 began to be significantly higher than that of Scheme 2 at around 107 seconds, with a trend similar to that of T4 temperature. This is because the heat from the EHC diffused to T5 after passing through the DOCoF. The T5 temperature of Scheme 1 reached a maximum of 338°C, while the maximum temperature of Scheme 2 was only 209°C. This is because the T4 temperature sensor of Scheme 1 is located at the front end of the EHC, so the temperature before the DOCoF is higher than the T4 temperature. Moreover, when the exhaust gas temperature reaches the oxidation temperature of the DOC (200°C), and the concentrations of HC and CO in the exhaust are high, according to the Arrhenius equation, the rate of the oxidation reaction increases exponentially with temperature, generating more heat. In contrast, the T4 temperature of Scheme 2 exceeded 200°C for only 99 seconds, and the maximum temperature did not exceed 210°C. The heat generated by the oxidation reaction was limited, mostly from the engine. Therefore, the T5 temperature of Scheme 1 was significantly higher than that of Scheme 2.

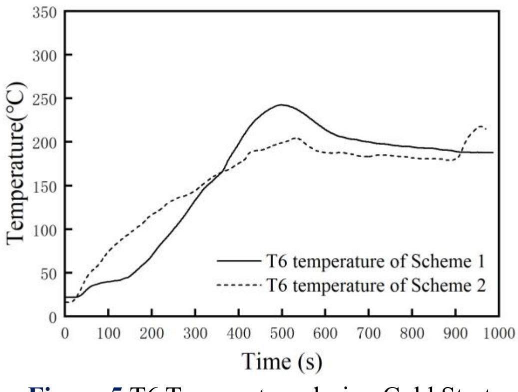

Figure 5 T6 Temperature during Cold Start

The figure 5 shows a comparison of T6 temperatures between the two schemes. The average temperature of Scheme 1 is 158°C, and that of Scheme 2 is 155.9°C. Additionally, the EHC of Scheme 2 was activated again at 873 seconds. Since the EHC of Scheme 2 is directly arranged in front of the T6 sensor, it directly heats T6 after being turned on. Therefore, the T6 temperature of Scheme 2 remained higher than that of Scheme 1 in the early stage of cold start. At 262 seconds, due to the DOC of Scheme 1 reaching the oxidation temperature and the delayed diffusion of heat from the front-end EHC, the temperature of Scheme 1 increased rapidly and exceeded that of Scheme 2 at 361 seconds.

3.2 NO_x Conversion Efficiency during Cold Start

An NO_x sensor is respectively arranged upstream of the DOC and downstream of the ASC in the exhaust after-treatment system. The upstream NO_x sensor is used to measure the original exhaust NO_x concentration (C_u), and the downstream NO_x sensor is used to measure the NO_x concentration in the treated tail exhaust. The sampling port of the PEMS device is located at the tail of the exhaust pipe, which can also measure the nitrogen oxide concentration in the tail exhaust (C_d). For accurate calculation, the value measured by the PEMS device is used here. The calculation method of NO_x conversion efficiency (η) is $\eta = \frac{C_u - C_d}{C_u} \cdot 100\%$.

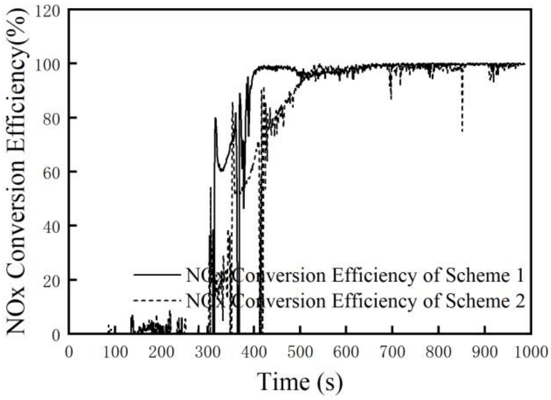

Figure 6 NO_x Conversion Efficiency during Cold Start

The figure 6 shows a comparison of NO_x conversion efficiency between two schemes. The average conversion efficiency of Scheme 1 is 64.82%, while that of Scheme 2 is 59.55%. Before 300 seconds, the after-treatment temperature was too low, and the overall conversion efficiency was close to 0, so this portion of the data is not analyzed in detail. At 317 seconds, the conversion efficiency of Scheme 1 shows a significant improvement, but urea injection does not begin until 377 seconds. During this period, the conversion efficiency ranges between 60% and 80%. This is due to the ammonia storage in the SCR system—when the temperature rises but has not yet reached the urea injection threshold (180°C), the urea in the SCR partially hydrolyzes to produce NH3, enabling partial $DeNO_x$ capability. After urea injection begins, the conversion efficiency increases rapidly and remains above 95%. Similarly, for Scheme 2, urea injection starts at 419 seconds. Between 305 seconds and 419 seconds, the DeNOx capability is attributed to ammonia storage.

3.3 Exhaust Temperature Characteristics During low-load conditions

The engine power in the trip stage is less than 10% of the maximum power, which is defined as the low-load condition. Among them, the low-load condition of Scheme 1 is 4,458 seconds, and that of Scheme 2 is 4,663 seconds.

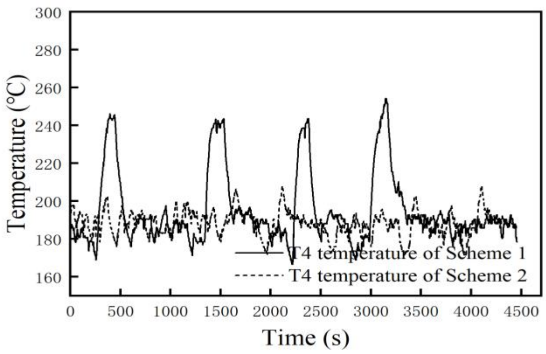

Figure 7 T4 Temperature during low-load Condition

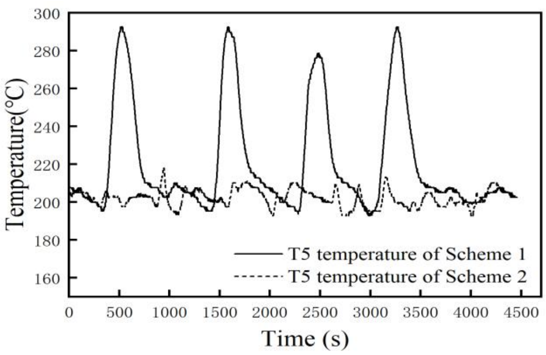

Figure 8 T5 Temperature during Low-load Condition

The figure 7 and 8 shows the temperature comparison of T4 and T5 between the two schemes. The average T4 temperature of Scheme 1 is 195.2°C, and the average T5 temperature is 220.5°C. The average T4 temperature of Scheme 2 is 188.2°C, and the average T5 temperature is 202.3°C. When the EHC of Scheme 1 is turned on, the temperature will rise to about 250°C, and when the EHC is turned off, the temperature will drop rapidly. Since the EHC of Scheme 2 is at the rear end, the T4 and T5 temperatures are not affected by its switching. Due to the oxidation reaction of DOCoF, the T5 temperature is higher than T4. Among them, the T5 temperature of Scheme 1 is 25.3°C higher than the average T4, and the T5 temperature of Scheme 2 is 14.1°C higher than the average T4. The temperature rise effect of Scheme 1 is better, which is because the front-end temperature of DOC in Scheme 1 is higher than that in Scheme 2.

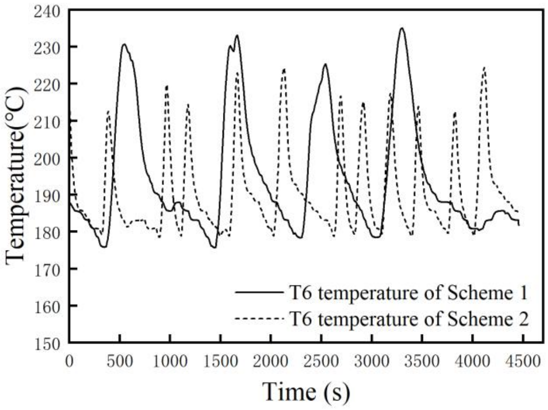

Figure 9 T6 Temperature during Low-load Condition

The figure 9 shows the temperature comparison of T6 between the two schemes. The average temperature of Scheme 1 is 194.8°C, and that of Scheme 2 is 190.4°C. When the EHC is turned on, the T6 temperature of Scheme 1 is higher, and its temperature retention capacity is better. However, when the EHC is turned on, the T6 temperature of Scheme 2 is lower, and its temperature retention capacity is poorer. In the low-load condition, Scheme 1 is turned on 4 times in total, with each activation lasting about 180 seconds, and the total activation time is 740 seconds. While Scheme 2 is turned on 11 times in total, with each activation lasting about 80 seconds, and the total activation time is 901 seconds.

3.4 NOx Conversion Efficiency During low-load conditions

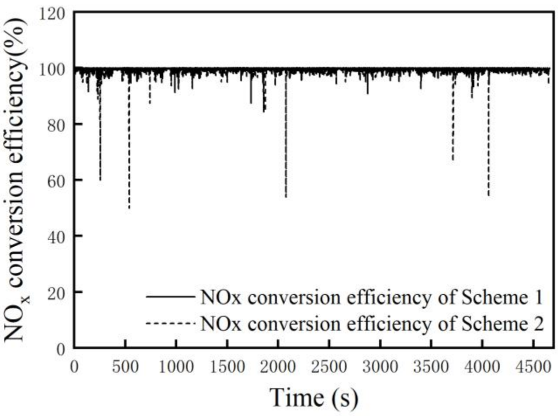

Figure 10 NOx Conversion Efficiency during Low-load Condition

The figure 10 shows the NOx conversion efficiency comparison between the two schemes. Due to the effect of the electric heating EHC, the average NOx conversion efficiency of both schemes under low-load conditions reaches more than 99%. As the EHC of Scheme 2 is frequently turned on and off, the conversion efficiency at some points where the T6 temperature is lower than 180°C is only about 60%. However, these points with low conversion efficiency have little impact on the overall conversion efficiency of the working conditions.

4 CONCLUSION

(1) In the entire test condition, the average T6 temperature of Scheme 1 is 188.1°C, and that of Scheme 2 is 184.4°C. The T6 temperature of Scheme 1 is 3.7°C higher than that of Scheme 2.

(2) In the cold-start condition, the urea injection time of Scheme 1 is 377 seconds, while that of Scheme 2 is 419 seconds. The urea injection time of Scheme 1 is 42 seconds earlier than that of Scheme 2, indicating that Scheme 1 has better NOx emission reduction capability under cold-start conditions. Its NOx conversion efficiency is 5.27%

higher than that of Scheme 2, and the NOx conversion efficiencies of the two schemes are close under low-load conditions.

(3) In the entire test condition, the total activation time of EHC for Scheme 1 is 1,142 seconds, while that for Scheme 2 is 1,407 seconds. The activation pattern of EHC in Scheme 1 features longer single activation duration and fewer activation times, whereas Scheme 2 shows shorter single activation duration and more activation times.

(4) Overall, Scheme 1 outperforms Scheme 2 in terms of temperature raising effect, NOx conversion efficiency, and EHC power consumption.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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ADAPTIVE CRUISE CONTROL CONSIDERING THE VARIABILITY OF THE LEADING VEHICLE'S DRIVING CONDITIONS

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Abstract: Due to the complex and variable driving conditions of the leading vehicle, it is difficult to control the distance between vehicles when following, resulting in poor driving comfort and safety. Based on this, this paper proposes an adaptive cruise control considering the variable driving conditions of the leading vehicle. Firstly, the longitudinal dynamics model of the self-vehicle is established using the Carsim software. Then, a safety distance model considering the speed of the vehicle in front is established, and the tracking control of the self-vehicle to the leading vehicle is realized based on model predictive control (MPC). Finally, the following vehicle simulation experiments are completed under different driving conditions of the leading vehicle. The results show that the adaptive cruise control strategy based on the improved safety distance model can achieve comfortable and safe following under different driving conditions of the leading vehicle.
Keywords: Adaptive cruise control; Model predictive control; Dynamics model; Safety distance model

1 INTRODUCTION

With China's vigorous efforts to liberate and develop productive forces, the living standards of the people have been continuously improving, and the number of cars purchased has been increasing. This has also led to many automobile traffic accidents. According to the survey, among a large number of automobile traffic accidents, those caused by rear - end collisions account for a relatively large proportion[1]. To solve this problem, experts and scholars at home and abroad have invested a great deal of energy. Adaptive Cruise Control (ACC) has received extensive attention due to its good performance in following - vehicle driving[2-5].

In terms of foreign research, Yang et al proposed a monocular - vision - based structure[6], TheNeoNet, structure, TheNeoNet, to improve the accuracy of speed estimation. On this basis, the soft Actor - Critic method was adopted to further optimize the vehicle - following strategy, achieving an improvement in the safety and comfort of the vehicle - following strategy and having good adaptability to various driving and following - vehicle scenarios. Chen et al proposed a multi - mode - switching - based intelligent vehicle multi - objective adaptive cruise control method based on a hierarchical control structure[7], fuzzy control theory, variable - spacing strategy, and particle swarm optimization algorithm, achieving an improvement in the driving safety, comfort, and fuel economy of the vehicle during cruising under multiple working conditions. Hu et al proposed a hierarchical adaptive cruise control strategy for vehicles[8]. The upper - layer controller calculates the expected vehicle output acceleration based on model predictive control and switches between speed and spacing control according to the driving conditions. The lower - layer controller uses the brake/throttle opening switching model, the inverse brake control model, and the inverse throttle opening model to obtain the expected throttle opening and brake pressure of the vehicle, thus achieving accurate and safe tracking of the target vehicle under different driving conditions. Chen et al proposed a model - predictive - control - based vehicle - following scheme based on the continuous comprehensive variable time - headway (CSVTH) model[9]. Compared with the existing three time - headway model - predictive - control - based vehicle - following schemes, the proposed CSVTH scheme has an economic improvement of 22.7%, a vehicle - following performance improvement of 38.8%, and a comfort improvement of 15.3%.

In terms of domestic research, He Liyang et al proposed a vehicle adaptive cruise control strategy based on model predictive control and improved active disturbance rejection control[10], which effectively weakened the impact on system control caused by changes in the vehicle itself or the external environment and improved the vehicle's adaptability and stability in following vehicles under different driving conditions. An Tingyu et al established an adaptive cruise control algorithm capable of predicting the acceleration of the vehicle in front based on a temporal convolutional network[11], effectively reducing the tracking error of the speed of the vehicle in front and the following - response time during the vehicle - following process. Li Shengqin et al proposed a hierarchically - designed adaptive cruise control strategy[12]. The upper - layer controller calculates the expected vehicle output acceleration based on the model predictive control algorithm, and the lower - layer controller calculates the expected vehicle torque based on the inverse longitudinal dynamics model, thus achieving stable and safe tracking of the target vehicle under multiple working conditions. Gu Zhiqiang et al proposed a multi - mode - switching control strategy based on fuzzy logic[13]. When the driving conditions of the vehicle in front are changeable, the ego - vehicle can achieve a smooth switch of the following - vehicle mode, effectively improving the accuracy of following - vehicle control.

From the above research, it can be seen that the current adaptive cruise control strategy is no longer only satisfied with studying the vehicle - following control under ideal conditions but also takes into account the variability of the driving conditions of the vehicle in front. Based on this, this paper proposes an adaptive cruise control considering the variability of the driving conditions of the vehicle in front. First, the longitudinal dynamics model of the ego - vehicle is built using Carsim software. Then, a safety inter - vehicle distance model considering speed is established, and the acceleration control of the ego - vehicle is achieved based on model predictive control (MPC). Next, the tracking control of the vehicle in front is completed according to the inverse longitudinal dynamics model of the ego - vehicle. Finally, vehicle - following simulation experiments are completed under different driving conditions of the vehicle in front. The results show that the adaptive cruise control strategy established based on the improved safety inter - vehicle distance model proposed in this paper can achieve comfortable and safe vehicle - following under different driving conditions of the vehicle in front.

2 ESTABLISHMENT OF VEHICLE DYNAMICS MODEL

The driving process of an automobile is complex and changeable. Different driving environments will lead to different driving behaviors of drivers. As one of the solutions for vehicle - following control, the adaptive cruise control strategy can effectively cope with different driving environments. In this paper, Carsim software is used to build the longitudinal dynamics model of the ego - vehicle to achieve the tracking control of the vehicle in front, enabling the ego - vehicle to follow the vehicle in front safely and comfortably[14]. The main interface of Carsim software for modeling is shown in Figure 1. The modeling process mainly consists of three parts: simulation conditions, solver, and vehicle parameter setting. After setting these three parts, a simulation experiment can be carried out to obtain the simulation results of the target vehicle under different working conditions[15].

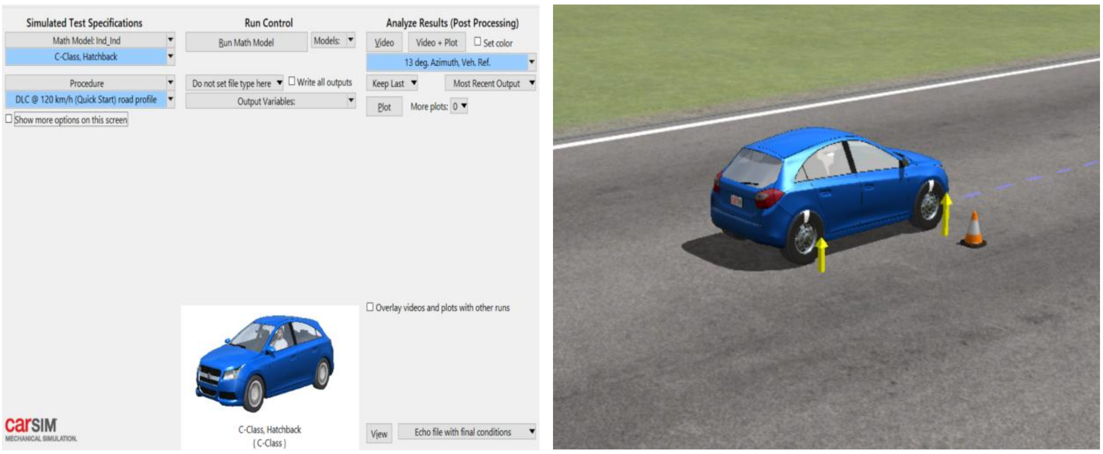

Figure 1 Main Interface of Carsim Modeling

This paper takes electric vehicles as the research object, establishes a vehicle model using some parameters of the Tesla Model 3 as the research vehicle parameters, and conducts adaptive cruise control simulation tests. Table 1 shows some parameters set in this model. In terms of layout, the rear-mounted rear-wheel drive scheme is adopted as the vehicle's driving mode.

Table 1 Vehicle Parameters

Parameter	Value
Curb weight	1760kg
Wheelbase	2875mm
Maximum power	194kw
Maximum torque	340N.m
Drag coefficient	0.22

3 ADAPTIVE CRUISE CONTROL STRATEGY

The overall flow of the adaptive cruise control strategy is shown in Figure 2, which consists of three parts: the safe inter-vehicle distance model, the MPC controller, and the inverse longitudinal dynamics model. First, the safe inter-vehicle distance model calculates the desired inter-vehicle distance based on the preceding vehicle information obtained from radar and cameras and the host vehicle information. Then, the MPC controller obtains the desired acceleration according to the desired inter-vehicle distance and the actual inter-vehicle distance obtained from radar and cameras. Finally, the inverse longitudinal dynamics model obtains the output torque of the vehicle based on the desired acceleration and the actual acceleration of the host vehicle, thereby realizing the control of the vehicle.

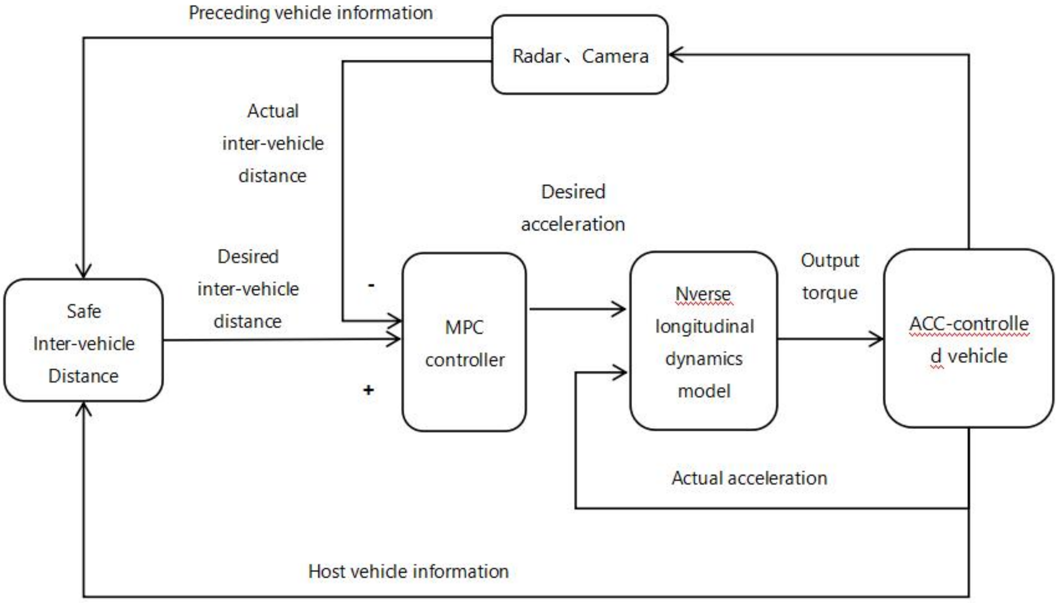

Figure 2 Overall Flow of Adaptive Cruise Control Strategy

3.1 Safe Inter-Vehicle Distance Model

The common safe inter-vehicle distance model in ACC strategies is an ideal inter-vehicle distance model, which does not consider the speed and acceleration of the preceding vehicle, but only the speed of the host vehicle, so that the inter-vehicle distance remains unchanged in a short time[16]. The specific formula is:

$$d_{exp}=v_{sel}t_1+d_{min} \quad (1)$$

Where: d_{exp} is the desired safe inter-vehicle distance between two vehicles; v_{sel} is the speed of the host vehicle; t_1 is the fixed inter-vehicle time headway, generally ranging from 1.5 to 2.0 s; d_{min} is the minimum safe inter-vehicle distance, generally ranging from 3 to 5 m.

In order to make the inter-vehicle distance model better adapt to different car-following conditions, this paper comprehensively considers the factors of the host vehicle speed and the preceding vehicle speed on the basis of the above common safe inter-vehicle distance. When the preceding vehicle speed v_{fro} is equal to the host vehicle speed v_{sel}, the host vehicle travels at a constant inter-vehicle distance; when $v_{fro} < v_{sel}$, the preceding vehicle speed is lower than that of the host vehicle, and the host vehicle needs to decelerate appropriately to increase the inter-vehicle distance to avoid collision; when $v_{fro} > v_{sel}$, the host vehicle should accelerate appropriately to reduce the following distance while ensuring safety. The specific formula is as follows:

$$d_{exp}=v_{sel}t_1+d_{min}-v_{rel}t_2+v_{sel}t_3^2 \quad (2)$$

Where t_2 and t_3 are constants greater than 0, and v_{sel} is the speed difference between the preceding vehicle and the host vehicle.

3.2 MPC Controller

3.2.1 Vehicle kinematic model

The schematic diagram of the longitudinal motion between vehicles is shown in Figure 3, where a_{sel} and a_{fro} are the accelerations of the host vehicle and the preceding vehicle respectively, v_{sel} and v_{fro} are the speeds of the host vehicle and the preceding vehicle respectively, and the following definitions are made:

$$\begin{cases} \triangle d=d-d_{exp} \\ v_{rel}=v_{fro}-v_{sel} \end{cases} \quad (3)$$

Where $\triangle d$ is the difference between the actual inter-vehicle distance d and the safe inter-vehicle distance, and v_{rel} is the speed difference between the preceding vehicle and the host vehicle.

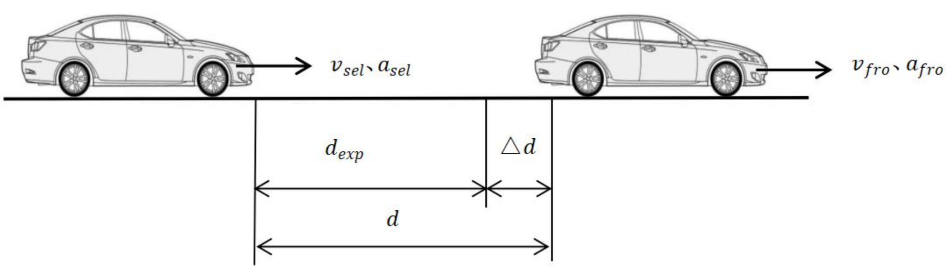

Figure 3 Schematic Diagram of Vehicle Longitudinal Motion

To eliminate the influence of time delay, a first-order inertial element is used to represent the relationship between the host vehicle acceleration a_{sel} and the desired acceleration a_{exp}:

$$a_{sel}=\frac{K_L}{T_L s+1}a_{exp} \tag{4}$$

Where: K_L is the system gain; T_L is the time constant; s is the Laplace operator.

Define the system state variables as $x(k)=[d(k),v_{sel}(k),v_{rel}((k),a_{sel}(k),j(k)]^T$, the system output vector as $y(k)=[\triangle d(k),v_{rel}((k),a_{sel}(k),j(k)]^T$, and $j(k)$ as the jerk of the host vehicle. Since it is difficult for sensors to accurately sense the acceleration of the preceding vehicle, and the acceleration of the preceding vehicle will affect the car-following control process of the host vehicle, the interference factor $w(\mathrm{k})$ of the preceding vehicle acceleration is added to establish the following discrete state space equations:

$$x(k+1)=Ax(k)+Ba_{exp}(k)+Gw(k) \tag{5}$$

$$y(k)=Cx(k)-D \tag{6}$$

Where: A, B, and C are coefficient space matrices, where $A=\begin{bmatrix}1 & 0 & T_s & -0.5T_s^2 & 0\\ 0 & 1 & 0 & T_s & 0\\ 0 & 0 & 1 & -T_s & 0\\ 0 & 0 & 0 & 1-\frac{T_s}{\mathrm{Y}} & 0\\ 0 & 0 & 0 & -\frac{1}{\mathrm{Y}} & 0\end{bmatrix}$, $B=\begin{bmatrix}0\\0\\0\\\frac{T_s}{\mathrm{Y}}\\\frac{1}{\mathrm{Y}}\end{bmatrix}$, $G=\begin{bmatrix}0.5T_s^2\\0\\T_s\\0\\0\end{bmatrix}$, T_s is the time interval between the previous and current moments of the host vehicle, and Y is the time constant, $C=\begin{bmatrix}1 & -t_1\text{-}t_3^2 & t_2 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}$, $D=\begin{bmatrix}d_{min}\\0\\0\\0\end{bmatrix}$.

3.2.2 Controller design

Due to the uncertainty of vehicle parameters, there will be a certain deviation between the predicted value and the actual measured value. Therefore, to improve the accuracy of the system, the prediction error $e(k)$ is introduced to correct Equation 5, resulting in the prediction equation:

$$x(k+1|k)=Ax(k)+Ba_{exp}(k)+GW(k)+He(k) \tag{7}$$

Where: $e(k)=x(k)\text{-}x(k|k\text{-}1), H=diag(\mathrm{h}_1,\mathrm{h}_2,\mathrm{h}_3,\mathrm{h}_4,\mathrm{h}_5)$ is the correction matrix, and the value range of each element in H is (0, 1).

From Equations 5 and 7, the vehicle prediction model can be derived:

$$\begin{cases} X_p(k+N_p|k)=A_p x(k)+B_p A_{exp}(k+N_c)+G_p W(k+N_p)+H_p e(k)\\ Y_p(k+N_p|k)=C_p x(k)+F_p A_{exp}(k+N_c)+S_p W(k+N_p)+L_p e(k)\text{-}D_p\end{cases} \tag{8}$$

Where: N_p is the prediction horizon; N_c is the control horizon; $X_p(k+N_p|k)$ and $Y_p(k+N_p|k)$ are the system state and output quantities from time k+1 to time $k+N_p$, respectively; A_p、B_p、G_p、H_p、C_p、F_p、S_p、L_p and D_p are all coefficient matrices of the prediction model; $A_{exp}(k+N_c)$ is the desired acceleration matrix; $W(k+N_p)$ is the system disturbance matrix.

During the MPC solution process, using hard constraints may result in no feasible solution[17]. To avoid this, this paper relaxes the hard constraints. Meanwhile, to prevent the constraint boundaries from expanding infinitely, a quadratic term of the slack factor is added to the objective function as a penalty. The objective function is established as follows:

$$\begin{aligned} J(k)=&\sum_{i=1}^{N_p}[y_p(k+i|k)\text{-}y_{ref}(k+i|k)]^{\mathrm{T}}\times Q[y_p(k+i|k)\text{-}y_{ref}(k+i|k)]+\\ &\sum_{i=1}^{N_p}a_{exp}{}^{\mathrm{T}}(k+i)Ra_{exp}(k+i)+\varepsilon^{\mathrm{T}}\rho\varepsilon\end{aligned} \tag{9}$$

$$\begin{cases} a_{min}+\varepsilon_1\delta_{min}^a\le a_{sel}(k)\le a_{max}+\varepsilon_1\delta_{max}^a\\ v_{min}+\varepsilon_2\delta_{min}^v\le v_{sel}(k)\le v_{max}+\varepsilon_2\delta_{max}^v\\ j_{min}+\varepsilon_3\delta_{min}^j\le j(k)\le j_{max}+\varepsilon_3\delta_{max}^j\\ a_{exp,min}+\varepsilon_4\delta_{min}^{a_{exp}}\le a_{exp}(k)\le a_{exp,max}+\varepsilon_4\delta_{max}^{a_{exp}}\end{cases} \tag{10}$$

Where:Q and R are weight coefficients; δ_{min}^a、δ_{min}^v、δ_{min}^j、$\delta_{min}^{a_{exp}}$ and δ_{max}^a、δ_{max}^v、δ_{max}^j、$\delta_{max}^{a_{exp}}$ are the slack coefficients for the upper and lower bounds of the system's hard constraints respectively; ε_1、ε_2、ε_3、ε_4 are slack factors; a_{min} and a_{max} are the minimum and maximum values of the host vehicle's acceleration respectively; v_{min} and v_{max} are the minimum and maximum values of the speed respectively; j_{min} and j_{max} are the minimum and maximum values of the jerk respectively; $a_{exp,min}$ and $a_{exp,max}$ are the minimum and maximum values of the control quantity respectively.

3.3 Inverse Longitudinal Dynamics Model

The key to longitudinal control lies in accurately obtaining the required torque of the host vehicle under different working conditions. Assuming that the vehicle is driving on a horizontal road surface, when the vehicle acceleration is known, the required torque of the vehicle can be derived inversely according to the longitudinal dynamics, specifically as follows:

$$\begin{cases} F_j = F_q - F_f - F_w \\ a_{exp} = \frac{1}{m\beta}\left(\frac{T_{exp} i_c \mu}{r} - mgf - \frac{1}{2} C_D A \rho v_{sel}^2\right) \\ F_q = \frac{T_{exp} i_c \mu}{r} \\ F_f = mgf \\ F_w = \frac{1}{2} C_D A \rho v_{sel}^2 \\ F_j = m\beta a_{exp} \end{cases} \tag{11}$$

Where: m is the total mass of the vehicle; β is the conversion coefficient of the vehicle's rotating mass; T_{exp} is the total expected torque of the motor; i_c is the total transmission ratio; μ is the motor efficiency; r is the wheel radius; f is the tire rolling friction coefficient; C_D is the air resistance coefficient; A is the windward area; and ρ is the air density.
The expected torque of the motor can be obtained from Equation 11:

$$T_{exp} = \frac{r[m(\beta a_{exp} + gf) + \frac{1}{2} C_D A \rho v_{sel}^2]}{i_c \mu} \tag{12}$$

4 SIMULATION VERIFICATION

Co-simulations were conducted using Carsim and Matlab/Simulink to verify the effectiveness of the control strategy designed in this paper under three working conditions: constant speed, deceleration, and acceleration. Figures 4, 5, and 6 show the simulation results of the host vehicle and the preceding vehicle under the corresponding working conditions, respectively.

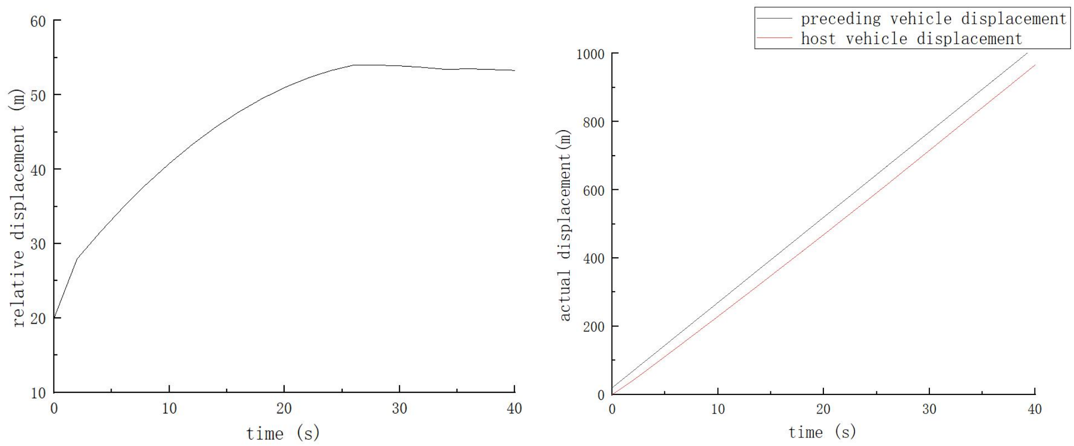

Figure 4 Simulation Setup for the Preceding Vehicle under Constant Speed Condition

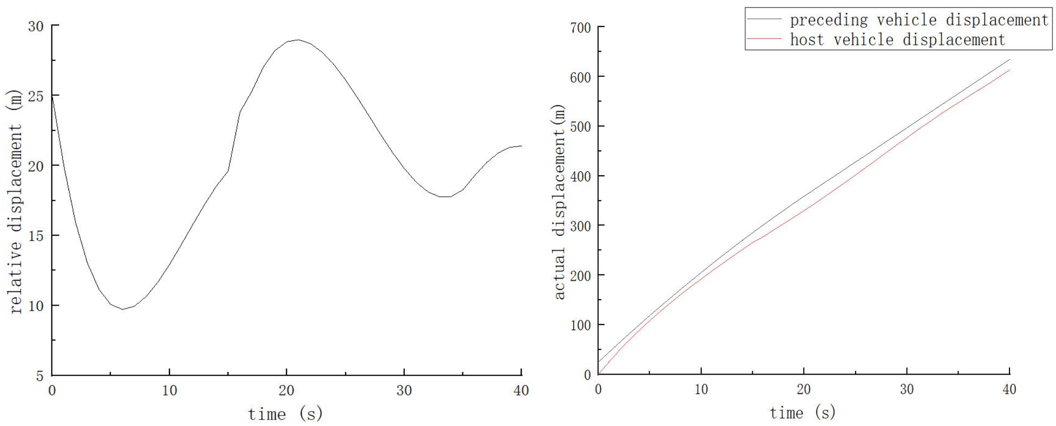

Figure 5 Simulation Setup for the Preceding Vehicle under Deceleration Condition

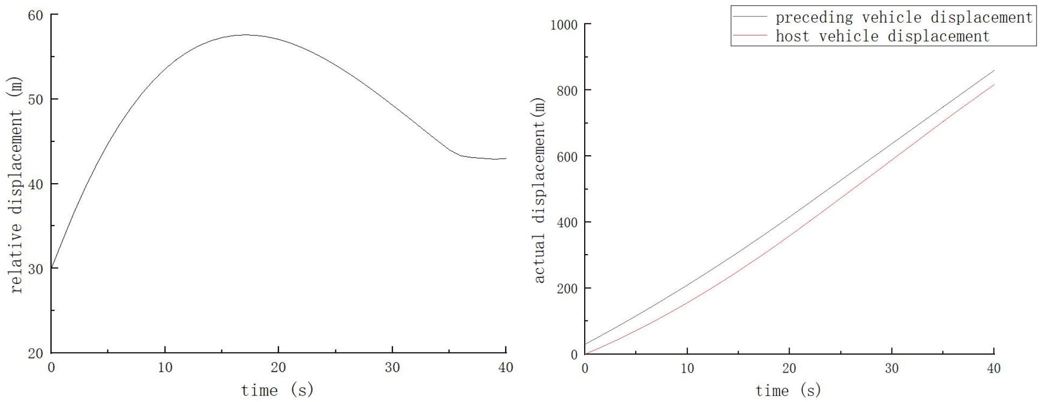

Figure 6 Simulation Setup for the Preceding Vehicle under Acceleration Condition

The simulation setup for the constant-speed condition is shown in Figure 4. At the start of the simulation, the distance between the preceding vehicle and the host vehicle is 20 meters. The preceding vehicle travels at a constant speed of 90 km/h, and the host vehicle follows at 75 km/h. To ensure effective following and improve road utilization, the host vehicle starts to accelerate. Since acceleration takes time, the inter-vehicle distance increases during this period. As the host vehicle's speed approaches that of the preceding vehicle, its acceleration gradually decreases, maintaining the distance between the two vehicles within a safe range.

The simulation setup for the deceleration condition is shown in Figure 5. At the beginning of the simulation, the preceding vehicle and the host vehicle are 25 meters apart. The preceding vehicle uniformly decelerates from 70 km/h to 50 km/h, while the host vehicle follows at 90 km/h. At this point, the sensors detect that the preceding vehicle is decelerating, and the actual inter-vehicle distance is much smaller than the desired safe distance, so the host vehicle starts to decelerate. The inter-vehicle distance first decreases and then increases, with a minimum distance of 9.7 meters, which well ensures the safety between the vehicles.

The simulation setup for the acceleration condition is shown in Figure 6. At the start of the simulation, the distance between the preceding vehicle and the host vehicle is 30 meters. The preceding vehicle is traveling at 60 km/h, and the host vehicle at 48 km/h. The preceding vehicle uniformly accelerates to 80 km/h. The host vehicle, recognizing that the preceding vehicle is accelerating and that its own speed is lower, also starts to accelerate, leading to an increase in the inter-vehicle distance. When the preceding vehicle begins to travel at a constant speed, the host vehicle gradually decelerates, causing the inter-vehicle distance to decrease and stabilize. The inter-vehicle distance shows a good response to changes in vehicle speed.

5 CONCLUSIONS

In this paper, the longitudinal dynamics model of the host vehicle is built using Carsim software. Then, a safe inter-vehicle distance model considering speed is established, and the acceleration control of the host vehicle is realized based on model predictive control (MPC). Furthermore, the tracking control of the preceding vehicle is completed according to the inverse longitudinal dynamics model of the host vehicle. Finally, co-simulations using Carsim and Matlab/Simulink are conducted to complete the car-following experiments under three working conditions of the preceding vehicle. The results show that the adaptive cruise control strategy proposed in this paper, which is based on the improved safe inter-vehicle distance model, can achieve comfortable and safe car-following under different driving conditions of the preceding vehicle.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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FROM CONCEPT TO MECHANISM: THE MODERN TRANSFORMATION PATH OF BIG DATA CRIME INVESTIGATION MODEL

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Abstract: The rapid development of big data technology has profoundly changed the landscape of criminal investigation. As a result, the big data criminal investigation model has emerged and become a key force in promoting the modernization of criminal justice. This paper conducts an in-depth analysis of the big data crime investigation model, elaborates on the characteristics of diversity, predictability, and correlational thinking it presents in the evolution of data thinking, and introduces key technologies such as crime data retrieval, collision, extraction, profiling, and relationship analysis that underpin this model. It also proposes establishing and improving compliance mechanisms (e.g., data collection, retrieval, review, supervision, and privacy protection) to ensure effective operation. The big data crime investigation model drives innovation in investigative concepts and methods, providing strong data support for investigative activities. Through optimizing concepts, technologies, and mechanisms, it will advance investigative work toward modernization, legalization, and intelligence.
Keywords: Big data criminal investigation; Data thinking; Key technologies; Compliance mechanism

1 INTRODUCTION

"Big data does not simply refer to large-scale data volumes, but rather to significant changes in epistemology and methodology[1]." Thanks to the rapid evolution of computer network technology and the exponential growth of network data, the "big data +" model is becoming increasingly mature, exerting a profound influence on various social fields. Notably, "big data + criminal justice" and "big data + criminal investigation" have become mainstream trends in the contemporary judicial field[2]. The benefits of applying big data technology in criminal investigations are increasingly prominent[3], and it has become a key driver of China's current criminal judicial reform. Thus, optimizing the big data crime investigation model is imperative in the new era.

2 THE EVOLUTION OF DATA-DRIVEN THINKING

Chinese police departments have widely adopted big data technology in criminal investigations, achieving significant results. The traditional information-driven investigation model is gradually transitioning to a big data-driven one, characterized by shifts from passive to proactive investigation, from individual to collaborative efforts, and from retrospective to predictive practices. This transformation has fundamentally changed investigative philosophy: traditional concepts such as "from case to person" and "from confession to evidence" are fading, while the new "from data to case" philosophy, reliant on big data platforms, is emerging as a trend. The big data-driven model demonstrates advantages in early warning, precise targeting, and comprehensive control. Thus, investigative departments and personnel should recognize the historical inevitability of this shift, break free from traditional constraints, and actively apply big data thinking to guide practice.

2.1 Diverse Thinking in Big Data Crime Investigation

In the era of big data, diverse thinking in crime investigation is reflected in the following three aspects: First, diversity in data acquisition. In traditional crime investigation models, investigators rely on the collection of physical information from crime scenes, such as "bodies, fingerprints, footprints, bloodstains, and DNA"; In contrast, big data-driven criminal investigations place greater emphasis on extracting crime-related information, with data acquisition shifting from physical crime scenes to virtual ones. Investigators can now collect additional crime-related information through sources such as "online shopping data, video footage, audio recordings, photographs, and social media platform information." Second, the diversity of data types. Traditional criminal investigations focused on the accuracy of crime-related information; in the big data-driven model, investigators emphasize the complexity and diversity of data types. Third, the diversity of data relationships. In traditional criminal investigations, causal relationships are a key logical basis for proving criminal facts; however, in the big data era, criminal investigations rarely consider causal relationships, instead emphasizing data associations. This approach mitigates the negative pursuit of causal relationships in traditional criminal investigations and reduces the adverse effects of unclear causal relationships on investigative activities.

2.2 Predictive Thinking in Big Data Crime Investigation

As a product of the big data era, the big data crime investigation model has driven criminal investigation activities to transition from labor-intensive to technology-intensive and data-intensive approaches. Compared to traditional crime investigation models, predictive crime investigation thinking is one of the core concepts of the big data crime investigation model. The greatest value of big data lies not in retrospectively analyzing the past or explaining the present, but in predicting the future[4]. As such, big data-driven criminal investigations have transcended traditional passive investigative models to achieve a functional transformation toward proactive criminal investigations. By applying machine learning to data regarding the "modus operandi, characteristics, and tools" of criminal activities or suspects within a specific spatio-temporal context, these investigations can predict and proactively identify potential criminal cases or activities, thereby realizing the predictive warning capabilities inherent in the big data-driven criminal investigation model.

2.3 Associative Thinking in Big Data Crime Investigation

In the era of small data, causal logic was the core thinking logic of traditional crime investigation models; in the era of big data, associative thinking is the core logic of big data crime investigation models. The associative thinking approach in the big data crime investigation model requires investigators to collect all data related to criminal offenses and analyze criminal cases using a systematic and holistic approach, breaking away from the traditional sampling data statistical methods in criminology, thereby enhancing the efficiency of criminal case resolution. Therefore, in the process of investigating criminal cases, the big data crime investigation model not only emphasizes causal logic but also places greater emphasis on the application of associative thinking. Through associative thinking, it further expands the scope of criminal investigation evidence collection, obtains additional criminal leads, and integrates criminal investigation resources, thereby promoting the healthy development of criminal investigation activities.

3 KEY TECHNOLOGIES

The big data crime investigation model differs from traditional crime investigation models in that it has a distinct "technical" characteristic, namely, it treats technology as the primary element throughout the entire crime investigation process. By searching, collating, and analyzing data, it further clarifies the facts of the crime and provides leads for crime investigation. In summary, the big data crime investigation model can rely on the following technologies or methods to carry out crime investigation activities.

3.1 Crime Data Retrieval Technology in Big Data Crime Investigation

Crime data retrieval technology is one of the most commonly used methods in the big data crime investigation model. Under this model, based on the type of data carrier, big data crime investigation can be divided into three categories: "database retrieval, internet retrieval, and electronic data retrieval." First, database retrieval primarily involves linking and retrieving data from various internal police department databases to identify criminal information. Additionally, other databases from the broader societal context can be appropriately utilized to seek out criminal information. This approach emphasizes data retrieval and criminal information mining within closed environments; Second, internet data retrieval. As is well known, the internet stores vast amounts of information available for investigators to extract[5]. Compared to database retrieval, internet data is more extensive, comprehensive, and open-source, with no restrictions on access. Investigators can utilize, extract, and save data at any time; Finally, electronic data retrieval. During the investigation and evidence collection process, when faced with a vast amount of electronic data, investigators can also utilize data retrieval to uncover new criminal information.

3.2 Crime Data Collision Technology in Big Data Crime Investigation

Crime data collision technology refers to investigators using computer algorithms and models to compare two or more databases or data sets closely related to criminal behavior and criminal information. The cross-referenced data and overlapping data generated by the collision are largely information related to criminal activity. Typically, crime data collision can be divided into the following stages: First, identifying the data objects and setting data tags. It is necessary to clearly define the data tags for obtaining the criminal information, such as "the identity characteristics, activity trajectories, and transportation information of the criminal suspect"; Second, screen the databases. By setting data tags, themes, and conditions, investigators further screen out data or information suspected to be related to criminal activities; Third, perform collision comparisons. Investigators match overlapping and cross-referenced data related to criminal activities based on the preliminary screening, reflecting the specific circumstances of the criminal suspect's criminal activities; Fourth, conduct in-depth analysis and judgment. Investigators Manually analyze and judge the aforementioned data to enhance data accuracy, thereby obtaining criminal leads and guiding the direction for subsequent criminal investigations[6].

3.3 Crime Data Extraction Technology in Big Data Crime Investigation

Data extraction and mining are core technologies in the current big data crime investigation model. Generally speaking, data mining technology is a key technology for automatically discovering criminal information. Investigators use various big data technologies such as machine learning and distributed computing to automatically identify and extract information related to crimes from massive amounts of data. There are various analysis methods and technologies, including “anomaly analysis, correlation analysis, spatio-temporal analysis, and clustering analysis.”

3.4 Criminal Data Profiling Technology in Big Data Crime Investigation

By employing big data analysis methods, this technology identifies the identity characteristics, activity patterns, and interpersonal relationships of criminal suspects, and describes them in the form of data. This provides criminal intelligence and leads to assist in solving cases, which is the essence of criminal data profiling technology in big data crime investigation[7]. Criminal data profiling is a step-by-step analytical process. On one hand, investigators must extract foundational information and data related to criminal activities from massive datasets. On the other hand, investigators must apply the aforementioned analytical techniques to summarize the foundational data, transforming it into more valuable insights. This enables the big data-driven criminal investigation model to characterize the basic circumstances of criminal suspects, thereby driving substantial progress in big data-driven criminal investigations.

3.5 Criminal data Relationship Analysis Technology in Big Data Crime Investigation

The big data crime investigation model emphasizes data interconnectivity as a foundation, using data analysis to reveal criminal relationship networks. The world today is an era of rapid information technology development, with internet technology reaching new heights. Social networks, applications, and other technologies have deeply integrated online activities into personal life. Criminal suspects' online activities leave traces, such as “interaction information with others, shared friends, and communication frequency” as data indicators. Through the analysis of these data technologies, the relationships among members involved in criminal activities can be further revealed. This analysis technology is more widely applied to organized criminal activities such as “terrorism, organized crime, and cross-border smuggling of firearms and ammunition.” Taking cross-border cybercrime as an example, an increasing number of suspects are now using the internet to communicate with one another, which provides a solid data foundation for the operation of criminal investigation models in the big data era.

4 ENSURING COMPLIANCE MECHANISMS

4.1 Establishing and Improving Data Collection Mechanisms for Big Data Crime Investigation

First, from the perspective of data collection sources in big data crime investigation, currently, criminal investigation departments primarily rely on commercial data models and platforms, leading to certain discrepancies in terms of “data collection standards, data updates, and data quality.” In line with the specific needs of criminal investigation departments: First, it is essential to establish and improve proprietary professional databases, standardize data standards, and ensure data quality to ensure that data effectively supports criminal investigation activities; Second, criminal investigation activities should make greater use of other official data to provide authentic data support for criminal investigations, avoiding the waste of investigative resources due to data verification; finally, data collection must balance comprehensiveness and authenticity. Big data crime investigations require data support; the more comprehensive the data, the more accurate the intelligence analysis, and the better the investigative outcomes.

Second, from the perspective of data collection standards in big data-driven criminal investigations, data collection standards vary across different regions, levels, police units, and departments, and data barriers inevitably exist[8]. Given the characteristics of different police units and departments, it is not feasible to enforce uniform standards and regulations for data sharing platforms, as this is a purely rational goal with an enormous engineering scope that is typically impossible to achieve. However, unified standards can be established based on common issues across police units to facilitate data sharing. Uniform data formats can also be established to convert all data into a standardized format, enabling data sharing and exchange between different police units. Additionally, common data security regulations can be established to conduct security reviews on shared data to prevent unauthorized use. Furthermore, common data update rules can be established to ensure timely data updates, maintaining data reliability and accuracy.

Third, from the perspective of data collection algorithms and models in big data crime investigation, the design of big data crime investigation data collection models is based on the summary of practical experience in crime investigation activities. These models are only deployed and applied in actual crime investigation and law enforcement activities after being validated through a large number of crime investigation cases and data, thereby possessing a certain degree of reliability. At the same time, once big data crime investigation algorithms and models are designed, they are not set in stone but require continuous improvement, supplementation, and revision through practical crime investigation activities. Additionally, to enhance crime investigation efficiency, it is necessary to continuously optimize big data crime investigation algorithms, integrate them with practical crime investigation activities, and further refine data algorithm models to better apply them to practical crime investigation activities.

4.2 Establish and Improve Data Retrieval Mechanisms for Big Data Crime Investigation

At present, big data crime investigation involves a vast amount of data information. To facilitate crime investigation departments and investigators in obtaining accurate and effective data services, it is necessary to establish and improve data retrieval mechanisms for big data crime investigation. On the one hand, data retrieval functions should be improved. Based on the needs of criminal investigation activities, further optimize the distribution of retrieval functions, remove modules with low usage frequency in actual operations, and add other required functions; on the other hand, it is crucial to accurately distinguish the authenticity of data information. The process and outcomes of big data-driven criminal investigations are directly influenced by the release and storage of data information. Therefore, the screening of genuine and fake data is particularly important. Genuine data can enhance the accuracy of predictive and analytical results in big data-driven criminal investigations, whereas fake data has little analytical value for criminal investigations. Therefore, by improving relevant mechanisms, investigators can obtain accurate and reliable case information from large amounts of data, eliminating the burden caused by fabricated information.

4.3 Establish and Improve the Data Review Mechanism for Big Data Crime Investigations

The data review mechanism in big data crime investigations involves third-party professional technical institutions using data cleaning and data verification methods to conduct legal, security, and technical reviews of the "data collection, data extraction, and data comparison" involved in big data crime investigations, thereby determining and verifying the authenticity and reliability of the data. This data review mechanism mainly includes two types: "case-by-case review" and "routine review." On one hand, case-specific review in big data crime investigations refers to situations where the parties involved in criminal proceedings proactively request a review for a specific case, or where legal supervision departments conduct a review of a case within their statutory authority. In such cases, third-party institutions review the compliance of big data crime investigation techniques and provide an impartial review conclusion for decision-making and reference by relevant departments. On the other hand, routine review is a mechanism based on the need for daily database maintenance, involving regular data cleansing and security checks. In big data crime investigation activities, establishing a sound data review mechanism can effectively maintain and enhance the accuracy of big data crime investigation data, provide technical support to legal supervision departments, and thereby achieve the technological and informatization development of legal supervision.

4.4 Establish and Improve the Data Supervision Mechanism for Big Data Crime Investigation

In big data crime investigation, the importance of data supervision is self-evident. Once data is lost or mismanaged, it will inevitably lead to irreparable errors in criminal investigations. On one hand, it is essential to prioritize database security, enhance security levels, and strengthen technical oversight to prevent cybercriminals from stealing data. On the other hand, in big data-driven criminal investigations, data collection must not infringe upon citizens' personal privacy rights. Personal information must not be collected arbitrarily, nor should citizens' privacy information be disclosed without proper authorization[9]. Criminal investigation departments must strictly manage, approve, and use data during its extraction and utilization processes. At the same time, it is also necessary to improve relevant remedial mechanisms. If violations or illegal disclosures of citizens' personal privacy occur during criminal investigations, the legal responsibility of the relevant parties should be pursued. Therefore, to effectively, safely, and legally constrain criminal investigation departments or investigators in the collection and use of citizens' information, should establish a national-level big data criminal investigation information control platform and set different permissions for criminal investigation departments at different levels, in different regions, and of different police types. Additionally, when collecting citizens' privacy data, technical oversight must be strengthened over criminal investigation departments or investigators during the process of collecting and using public privacy data. The relevant regulatory authorities must use technical means to clearly track the entire process of data collection, use, and deletion, as well as the associated traces, to hold violators accountable for their actions.

4.5 Establish and Improve Mechanisms to Protect Privacy Rights in the Investigation of Big Data Crimes

First, the status of personal information rights in criminal justice must be clarified. With the development of technology, the security of personal information has become increasingly important. Criminal justice practice requires relevant organizations and individuals to protect citizens' personal information, especially their personal privacy information. Therefore, criminal investigation departments need to further strengthen the concept of protecting citizens' privacy rights, effectively increase the protection of citizens' information, and emphasize its status in criminal justice. In summary, protecting personal information rights as a fundamental right of citizens in the criminal justice system, and regulating the collection and processing of citizens' personal information by criminal investigation departments or investigators as statutory investigative measures, is of critical importance for standardizing the operation of big data crime investigations.

Second, strictly regulate the system for collecting and using personal information. In big data criminal investigations, criminal investigation departments should establish strict systems for the collection and use of personal information, and collect and use citizens' personal information in accordance with the principle of proportionality in investigations, in compliance with laws and regulations. From the perspective of the legislative framework for investigations, on the one hand, relevant laws and regulations such as the Personal Information Protection Act should be improved to further standardize the collection and use of personal information, ensuring strict approval, management, and use. On the other hand, the entities authorized to use personal information should be strictly defined. In big data-driven criminal investigations, only investigative personnel directly involved in handling criminal cases may use citizens' personal information, but they must first obtain approval through the proper approval procedures. Only after obtaining approval may they utilize big data technology to query, link, and use personal information. Under no circumstances may they arbitrarily query or use citizens' private information[10].

Third, establish a redress system for citizens' privacy rights. To establish a fair and comprehensive system for protecting citizens' privacy rights, big data criminal investigation personnel must resolutely implement relevant legal regulatory measures, strictly conduct big data criminal investigations in accordance with laws, regulations, and rules, and must not infringe upon citizens' privacy rights through any improper means. Big data crime investigators are the litigation subjects responsible for safeguarding citizens' personal privacy rights. On one hand, it is necessary to strengthen the professional competence of big data crime investigators to ensure that citizens' personal privacy rights are effectively protected. On the other hand, any leakage of citizens' personal information resulting from erroneous investigative actions or activities must be strictly held accountable. Additionally, a remedial system must be established to safeguard citizens' privacy rights.

5 CONCLUSION

As discussed above, the big data-driven criminal investigation model represents a major transformation in China's criminal justice system, fundamentally altering investigative concepts, evidentiary frameworks, and operational measures, and providing robust data-driven support for current criminal investigation activities. By objectively, fairly, and rationally understanding the big data-driven criminal investigation model and continuously improving and optimizing it through "conceptual transformation, technological reliance, and institutional safeguards," we aim to drive the ongoing modernization, legalization, and intelligentization of criminal investigation activities in the current stage.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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ROBOTIC-ASSISTED VERSUS CONVENTIONAL LAPAROSCOPIC PYELOPLASTY FOR PEDIATRIC URETEROPELVIC JUNCTION OBSTRUCTION: A META-ANALYSIS

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Abstract: Background: The application of robot-assisted laparoscopic surgery (RALP) in paediatric urology is increasing, but there is still controversy about the efficacy and safety of RALP compared to traditional treatment assisted laparoscopic surgery (LAP) in increasing obstructive uropathy at the ureteropelvic junction (UPJO) in children. This meta-analysis of effects to evaluate and evaluate the clinical efficacy of robot-assisted laparoscopic surgery (RALP) and paediatric pyeloplasty in laparoscopic treatment of UPJO, A computer search was conducted in English as PubMed, Cochrane database, Web of Science, OVID, and in Chinese databases as Sinomed, China National Knowledge Infrastructure (CNKI), Weipu database, and Wanfang databases for relevant literature, with categorical dates up to December 2024. The Man 5.4 variables were used for meta-analysis of the literature data. For risk ratio, the literature (RR) was used as the reference database, RevMan used for statistical measures, such as statistical databases. The mean (MD) was conducted. Descriptive analysis was conducted for patients with less literature and postoperative data. Results: A total of 13 studies were included, with 916 cases, all undergoing pyeloplasty. RALP superiority aspects over traditional laparoscopic surgery in the following surgical success rate [RR = 1.04, 95% CI (1.01, 1.07)], ureteropelvic anastomosis [MD = -27.39, 95% CI (-44.33, -10.46)], postoperative retention time [MD = -1.00, 95% CI (-1.42, -0.58)], stay insufficient [MD = -1.17, 95% CI (-1.82, -0.52)], intraoperative blood loss [MD = -2.98, 95% CI (-4.77, -1.19)], and reoperation rate [RR = 0.38, 95% CI (0.16, 0.87)], all statistically significant differences after renal surgery ($P < 0.05$). RALP had significant differences compared to traditional higher [MD = 2.68, 95% CI (1.78, 3.58)] ($p < 0.05$), which showed significant posterior ior-changes (APD) and laparoscopic surgery [MD = -0.08, 95% CI (-0.26, 0.10)], statistically significant split function (GRF) [MD = 0.69, 95% CI (-1.85, before laparoscopic surgery] 3.24)], operating time [MD = -9.8, 95% CI (-24.04, 4.44)], postoperative complications [RR = 0.70, 95% CI (0.43, 1.14)], and follow-up time [MD = 0.08, 95% CI (-3.33, 3.49)] showed no statistically significant differences ($P > 0.05$). Conclusion: With pyeloplasty, pyeloplasty has a significant effect in treating renal paediatric vis-ureter obstruction groups, laparoscopic pyeloplasty has been compared with conventional pyeloplasty. pelvis-ureter anastomosis shorter time, less bleeding, shorter duration of postoperative drainage, lower reoperation rates, and shorter postoperative hospital stays. This robotic-assisted pyeloplasty has been shown to result in a higher success rate, faster recovery rates, and long-term better surgical outcomes. However, due to high hospital discharge, this remains certain in its application.
Keywords: Ureteropelvic junction obstruction; Robotic surgery; Laparoscopy; Treatment outcome; Meta-analysis

1 INTRODUCTION

Ureteropelvic junction obstruction (UPJO) is the most common cause of hydronephrosis in children and a common congenital malformation of the urinary system in children, with an incidence of 1/800 – 1/600[1-2] . It is often detected in infancy that previous open Ander-son-Hynes pyeloplasty is the treatment of choice for UPJO, with a success rate of more than 90% [3] . In recent years, with the development and popularization of minimally invasive surgical techniques, traditional laparoscopic pyeloplasty (LP) and robot-ic-assisted laparoscopic pyeloplasty (RALP) have played an important role in the treatment of UPJO. Compared with open pyeloplasty, laparoscopic pyeloplasty has less trauma, faster recovery, and the success rate of surgery is not lower than traditional open surgery [1-2] . However, the abdominal cavity space of children is limited, endoscopic suture and knotting is technically demanding for surgeons, and the learning curve is relatively long [2]. However, Da Vinci robot-assisted laparoscopic surgery has higher flexibility, stronger stability, more efficient operation, and is more conducive to fine operations such as endoluminal anatomical separation and suture knotting [4]. In this study, Meta-analysis will be used to comprehensively evaluate the effect of RALP and LP in the treatment of UPJO.

2 MATERIALS AND METHODS

2.1 Literature Inclusion and Exclusion Criteria

1. Inclusion criteria ① The study subjects were newborns and children; ② The study content was robot-assisted laparoscopic surgery or traditional laparoscopic surgery in the treatment of ureteropelvic junction obstruction in children; ③The success criteria of surgery were the disappearance or alleviation of clinical symptoms after surgery and during follow-up, urinary ultrasonography showed improvement of hydronephrosis and improvement of drainage curve on the renogram [5]. 2. Exclusion criteria: ① The study subjects are adults; ② The studies of RALP or LP in the treatment of UPJO are simply included; ③ The repeated literatures or literature data are incomplete; ④ Multiple studies from the same center, with repeated data; ⑤ Case reports, animal experiments, reviews or systematic reviews, conference proceedings and literatures with too low quality evaluation; ⑥ The study contents or indicators are inconsistent.

2.2 Search Strategy

Two searchers independently searched. English databases (PubMed, Cochrane database, Web of Science, Ovid, Embase) and Chinese databases (CNKI, VIP database, CBM, Wanfang database) were searched by computer system. English Search terms: Ro-botic/Robot-assisted, Pyeloplasty, Children/Pediatric, Ureteropelvic junction obstruction; Chinese search terms: robotic, pyeloplasty, pediatric, ureteropelvic junction obstruction. The literature was published until December 2024.

2.3 Data Extraction, Outcome Measures and Quality Evaluation

Two reviewers read the titles and abstracts of the articles, screened the articles according to the inclusion criteria and exclusion criteria, then searched and read the full text, independently extracted the data, and cross-checked them. The extracted contents included: ① basic information of the study: first author, publication year, study region, article source, sample size, age, gender, lesion side, and follow-up time; ② outcome indicators of the study: success rate of surgery, incidence of postoperative complications, operation time, ureteropelvic anastomosis time, preoperative and postoperative renal pelvis anteroposterior diameter (APD) value, preoperative and postoperative renal function (GRF) value, intraoperative blood loss, postoperative drainage tube indwelling time, hospital stay, hospitalization costs, and postoperative follow-up time. Literature quality evaluation refers to Newcastle-Ot-tawa (NOS) evaluation scale, including selection (4 points), comparability (2 points) and outcome (3 points); it is divided into low risk (7 ~ 9 points), moderate risk (4 ~ 6 points) and high risk (1 ~ 3 points); the literatures with NOS score < 5 points are excluded. Fourth, statistical processing was performed using RevMan 5.4 to analyze the data. Heterogeneity tests were performed for each study, and if $P \geq 0.1$ and $I^2 < 50\%$, each study was considered homogeneous and a fixed-effect model was selected; if $P < 0.1$ and $I^2 \geq 50\%$, each study was considered heterogeneous and a random-effect model was selected. RR was used as the analysis statistic for dichotomous variables; weighted mean difference (MD) was used as the analysis statistic for continuous variables. Descriptive analysis is adopted for the study indicators with few included literatures and incomplete data.

3 RESULTS

3.1 Literature Search Results

According to the search strategy, 789 literatures were obtained, and 776 literatures were excluded, including 262 repeated literatures, 496 case reports, animal experiments, reviews or systematic reviews, conference proceedings and unrelated literatures, 18 literatures inconsistent with the content of this article, incomplete data and low quality evaluation, and finally 13 studies were included [3-4, 6-13]. Literature search results and flow are shown in Figure 1.

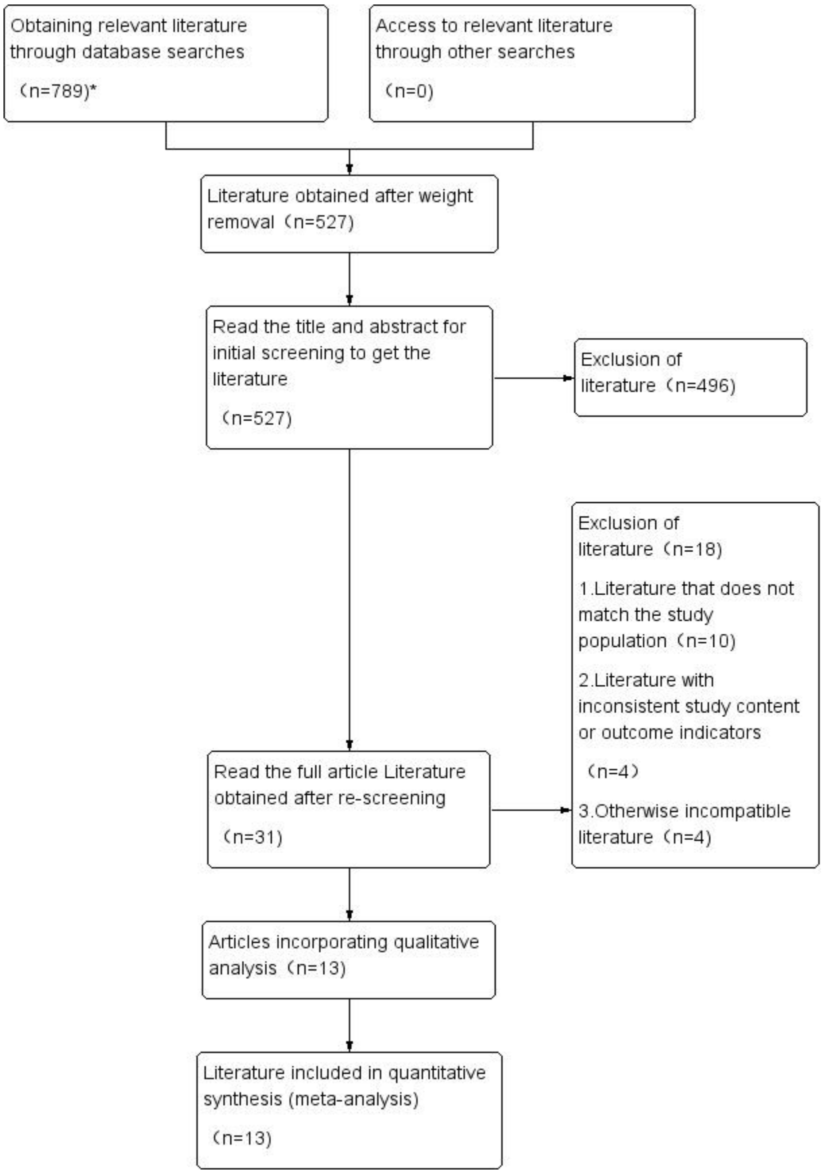

Figure 1 Literature Search Process and Results

*Note: The databases searched and literature data retrieved were as follows: PubMed (n = 172), EMbase (n = 61), The Cochrane Library (n = 9), OVID (n = 312), Web of Science (n = 41), Sinomed (n = 39), CNKI (n = 95), Wanfang Database (n = 37), and VIP Database (n = 23).

3.2 Basic Characteristics of Cases in the Included Study Literatures

Among the 13 included literatures, 12 literatures were retrospective cohort study and 1 was randomized controlled study, with a total number of 916 cases, including 489 cases of robot-assisted laparoscopic surgery and 427 cases of traditional laparoscopic surgery [10]. The basic characteristics of literature cases included in the meta-analysis are shown in Table 1, and the surgery-related indicators of literature donations included in the study are shown in Table 2 [3-4, 6-13].

Table 1 Literature Characteristics of Included Studies

Included study article presentation	Study region	Number of cases		Age at surgery (months) [a]		Follow-up Time (months) [b]	
		RALP Group	LP Group	RALP Group	LP Group	RALP Group	LP Group
Li Yixuan et al, 2023[8]	CHINA	21	42	48.55	84.69	16.57	16.39
Liu Hui et al, 2023[7]	CHINA	22	48	87.64	64.79	NR	NR

Qi Liu et al, 2023[6]	CHINA	31	32	57.35	50.09	NR	NR
Li Qian et al, 2024[9]	CHINA	27	20	79.20	78.00	12.8	11.4
Yiqing Lv et al, 2019[4]	CHINA	15	24	90.00	38.40	17.5	22.3
Patel et al, 2016[14]	USA	55	13	93.96	81.91	NR	NR
Esposito et al, 2019[3]	Italy	37	30	93.47	31.35	21.13	19.52
Koga et al, 2023[15]	JAPAN	22	34	88.8	94.8	NR	NR
González et al, 2022[16]	USA	174	86	106.43	123.02	46.67	41.58
Silay et al, 2020[12]	Tulki	26	27	53.66	30.50	10.50	14.26
Sun et al, 2023[11]	CHINA	12	21	18.34	11.90	100	100
Tam et al 2018[10]	CHINA	26	37	38.74	28.74	24.77	38.05
Neheman et al 2018[17]	Israel	21	13	6.03	5.88	14.09	5.65

*Note: NR indicates not reported; a indicates mean age at operation; b indicates mean follow-up time; RALP: robot-assisted laparoscopic pyeloplasty; LP: conventional laparoscopic pyeloplasty; UPJO: ureteropelvic junction obstruction

Table 2 Surgery-Related Indicators of UPJO Cases Included in Study Article

Literature included in the study	Surgical time (x±s,min)		Renal pelvic-ureteral anastomosis time (x+s,min)		Postoperative complications (cases)		Reoperation (cases)	
	RALP Group	LP Group	RALP Group	LP Group	RALP Group	LP Group	RALP	LP
Li Yixuan et al,, 2023[8]	252.6±39.00	231.28±46.06	135.60±22.80	131.92±32.23	1	2	0	0
Liu Hui et al, 2023[7]	152.05±38.63	140.44±37.25	27.95±9.52	41.17±8.34	2	4	0	0
Qi Liu et al, 2023[6]	119.87±15.64	128.53±36.27	NR	NR	4	6	0	0
Li Qian et al, 2024[9]	153.0±14.4	189.9±32.6	68.8±16.8	97.5±12.0	1	3	0	0

Yiqing Lv et al，2019[4]	173±31	167±25	NR	NR	1	1	1	1
Patel et al，2016[14]	231.70±46.13	264.62±40.86	NR	NR	2	0	0	1
Esposito et al，2019[3]	137.10±24.70	155.89±44.11	77.84±11.53	104.19±12.25	0	1	0	1
Koga et al，2023[15]	305.2 ± 50.1	340.0 ± 117.9	60.2 ± 13.8	133.0 ± 31.6	0	4	0	4
González et al，2022[16]	183.28±47.05	148.75±61.56	NR	NR	2	2	2	2
Silay et al，2020[12]	105.19±22.87	139.26±43.21	NR	NR	2	2	0	2
Sun et al，2023[11]	120.25 ± 37.54	156.10 ± 51.11	NR	NR	0	0	0	1
Tam et al，2018[10]	251.80±53.01	250±58.81	NR	NR	4	6	1	3
Neheman et al，2018[17]	164.98±32.81	181.49±39.15	NR	NR	5	4	1	1

*Note: The operation time of RALP group included the time of mechanical installation; NR: not reported; RALP: robot-assisted laparoscopic pyeloplasty; LP: traditional laparoscopic pyeloplasty; UPJO: ureteropelvic junction obstruction

3.3 Meta-Analysis Results

3.3.1 Surgical success rate

A total of 9 literatures recorded the success rate of two surgical methods, heterogeneity test result $\chi 2 = 4.71$, I 2 = 0%, P = 0.79, using fixed effect model. The success rate of surgery in the RALP group was higher than that in the LP group, and the difference was statistically significant [RR = 1.04, 95% CI (1.01, 1.07), P = 0.02] [3-4, 10-15, 17] (Figure 2).

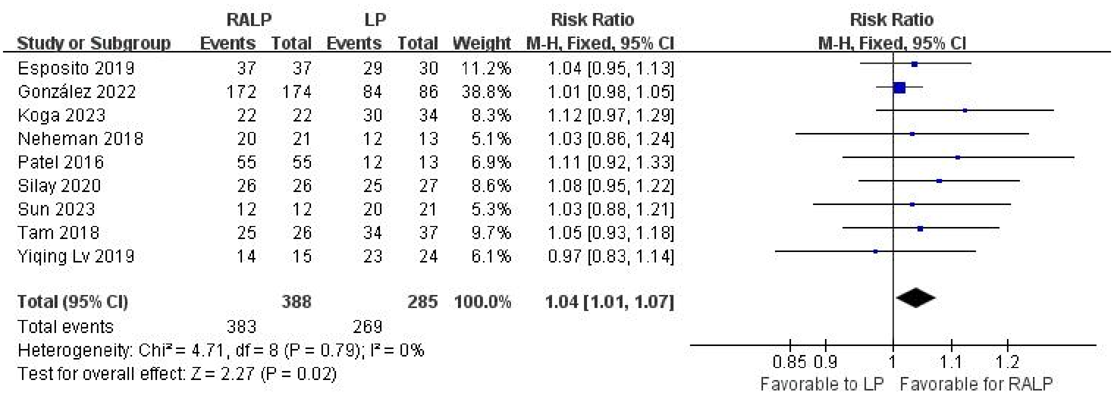

Figure 2 Meta-Analysis of Success Rates of RALP and LP Procedures for Ureteropelvic Junction Obstruction RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.2 Pelvoureteropelvic anastomosis time

There were 5 literatures comparing pyeloureteral anastomosis time between the two surgical methods, heterogeneity test result $\chi 2 = 99.74$, I 2 = 96%, P < 0.00001, using random effect model. The ureteropelvic anastomosis time in the RALP group was shorter than that in the LP group, and the difference was statistically significant [MD = -27.39, 95% CI (-44.33, -10.46), P = 0.002] [3, 7-9, 15] (Figure 3).

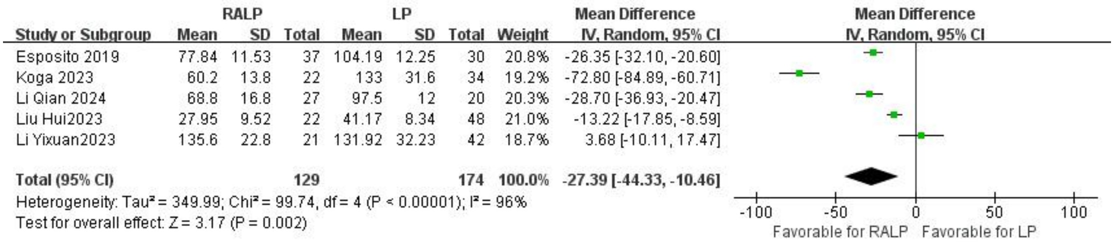

Figure 3 Meta-Analysis of Ureteropelvic Junction Obstruction RALP and LP Ureteropelvic Anastomosis Time RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.3 Intraoperative blood loss

Five literatures compared intraoperative blood loss between two surgical methods, heterogeneity test result χ 2 = 29.39, I 2 = 86%, P < 0.00001, using random effect model. Intraoperative blood loss was less in the RALP group than in the LP group, and the difference was statistically significant [MD = -2.98, 95% CI (-4.77, -1.19), P = 0.001] [6-9, 15] (Figure 4).

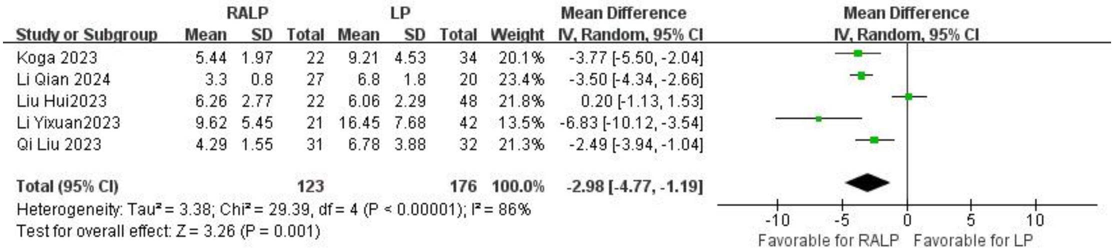

Figure 4 Meta-Analysis of Intraoperative Blood Loss of Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.4 Postoperative drainage tube indwelling time

There were 3 literatures comparing postoperative drainage tube indwelling time between two surgical methods, heterogeneity test result χ 2 = 3.40, I 2 = 41%, P = 0.18, using fixed effect model. The postoperative drainage tube indwelling time in RALP group was shorter than that in LP group, and the difference had statistical significance [MD = -1.00, 95% CI (-1.42, -0.58), P < 0.00001] [6, 11, 15] (Figure 5).

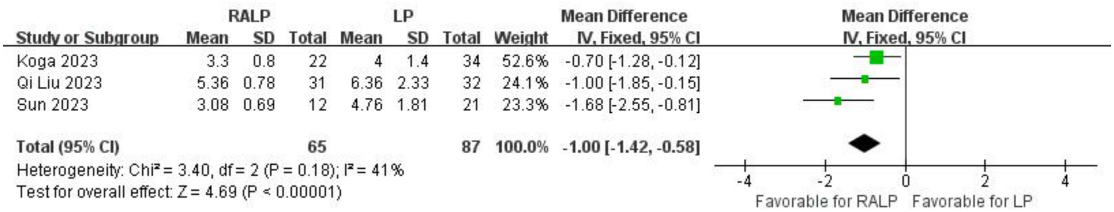

Figure 5 Meta-Analysis of Drainage Tube Indwelling Time after Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.5 Postoperative hospital stay

12 papers compared the postoperative hospital stays between two surgical methods, heterogeneity test results χ 2 = 198.03, I 2 = 94%, P < 0.00001, using the random effect model. Postoperative hospital stay was shorter in the RALP group than in the LP group, and the difference was statistically significant [MD = -1.17, 95% CI (-1.82, -0.52), P = 0.0004] [3, 6-12, 14-17] (Figure 6).

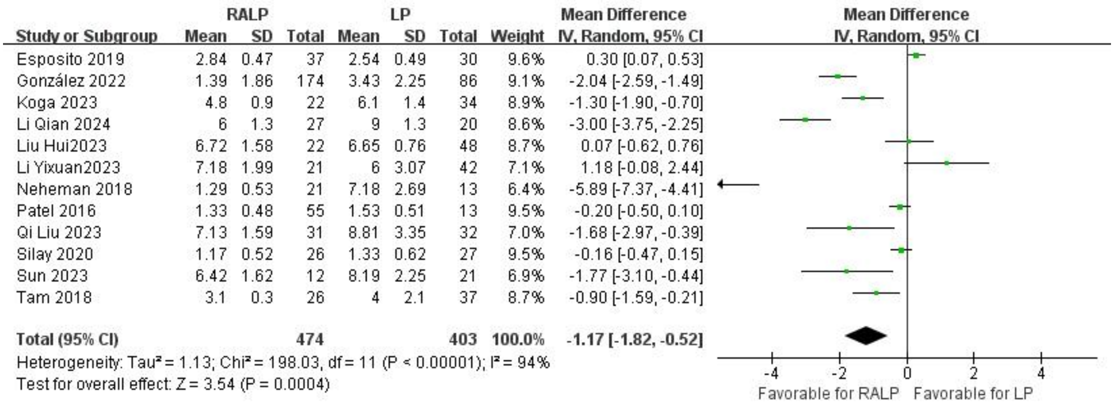

Figure 6 Meta-Analysis of Length of Stay after RALP and LP for Ureteropelvic Junction Obstruction RALP and LP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.6 Reoperation rate

Nine papers compared the reoperation rates between the two surgical methods, with heterogeneity test results χ 2 = 2.80, I 2 = 0%, P = 0.95, using a fixed-effect model. The incidence of reoperation in the RALP group was lower than that in the LP group, and the difference was statistically significant [RR = 0.38, 95% CI (0.16, 0.87), P = 0.02] [3-4, 10-15, 17] (Figure 7).

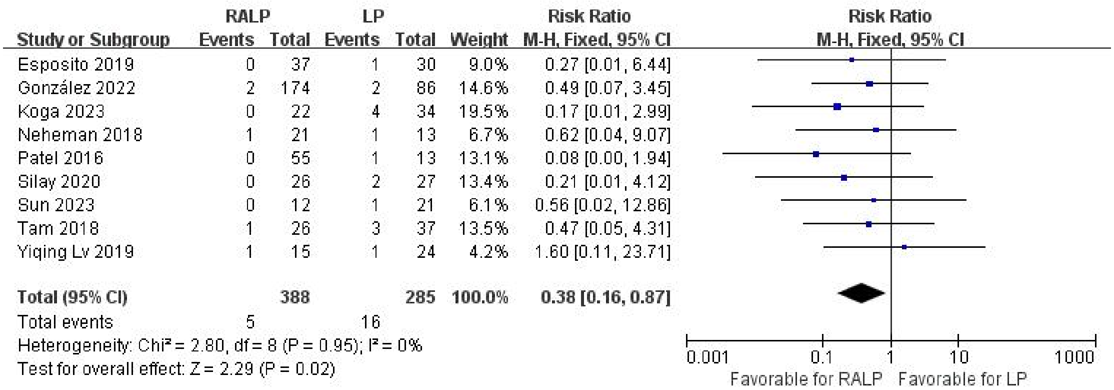

Figure 7 Meta-Analysis of Reoperation Rates for Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.7 Hospitalization costs

There were 4 literatures comparing hospitalization costs between the two surgical methods, heterogeneity test result χ 2 = 304.41, I 2 = 99%, P < 0.00001, using random effect model. Hospitalization costs were higher in the RALP group than in the LP group, and the difference was statistically significant [MD = 2.68, 95% CI (1.78, 3.58), P < 0.00001] [6-7, 9, 11] (Figure 8).

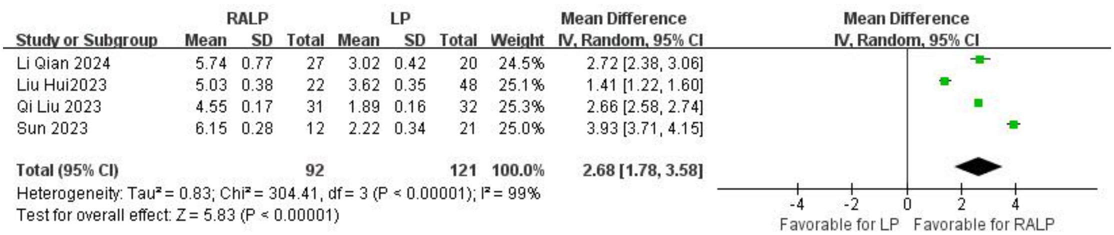

Figure 8 Meta-Analysis of Hospital Costs for Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.8 Changes in anteroposterior diameter (APD) of renal pelvis before and after operation

Eight papers compared the changes in anteroposterior diameter (APD) values of the renal pelvis between the two surgical methods, and the heterogeneity test results were χ 2 = 5.74, I 2 = 0%, and P = 0.57, using a fixed-effect model. The decrease in APD values before and after surgery in the RALP group was significantly higher than that in the LP group, but the difference was not statistically significant [MD = -0.08, 95% CI (-0.26, 0.10), P = 0.40] [3, 6-12] (Figure 9).

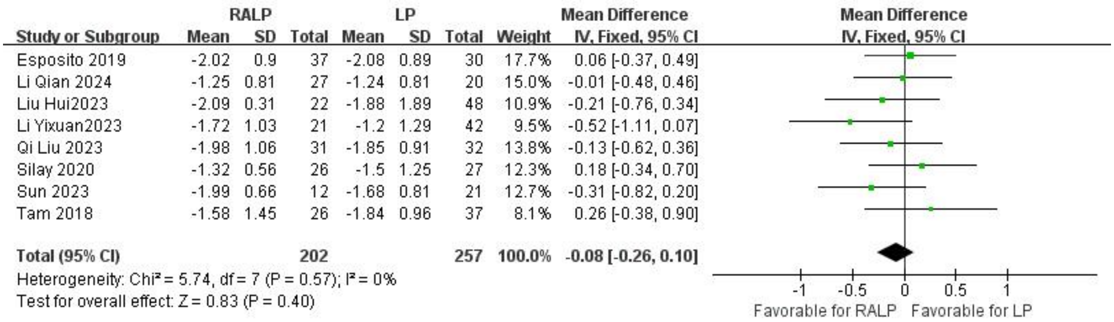

Figure 9 Meta-Analysis of APD Value Changes before and after Ureteropelvic Junction Obstruction RALP and LP Surgery RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.9 Changes of renal function (DRF) before and after operation

There were 3 literatures comparing the change of renal function (DRF) between the two surgical methods, heterogeneity test result χ 2 = 2.19, I 2 = 9%, P = 0.33, using fixed effect model. The change of renal function (DRF) before and after operation in the RALP group was not significantly different from that in the LP group [MD = 0.69, 95% CI (-1.85, 3.24), P = 0.59] [8-10] (Figure 10).

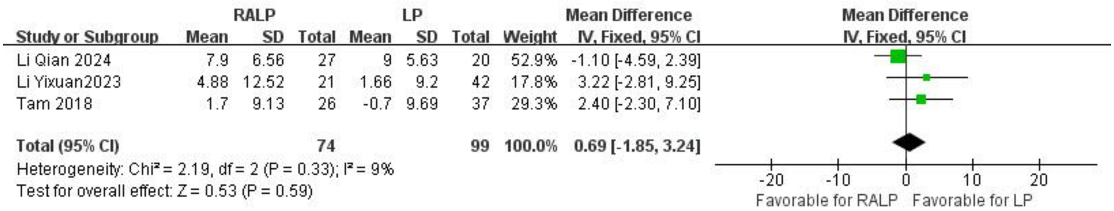

Figure 10 Meta-Analysis of Fractional Renal Function (DRF) Changes before and after Surgery for Ureteropelvic Junction Obstruction RALP and LP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.10 Surgery time

Thirteen literatures compared the operation time between two surgical methods, heterogeneity test result χ 2 = 76.88, I 2 = 84%, P < 0.00001, using random effect model. Operative time was shorter in the RALP group than in the LP group, but the difference was not statistically significant [MD = -9.8, 95% CI (-24.04, 4.44), P = 0.18] [3, 4, 6-13] (Figure 11).

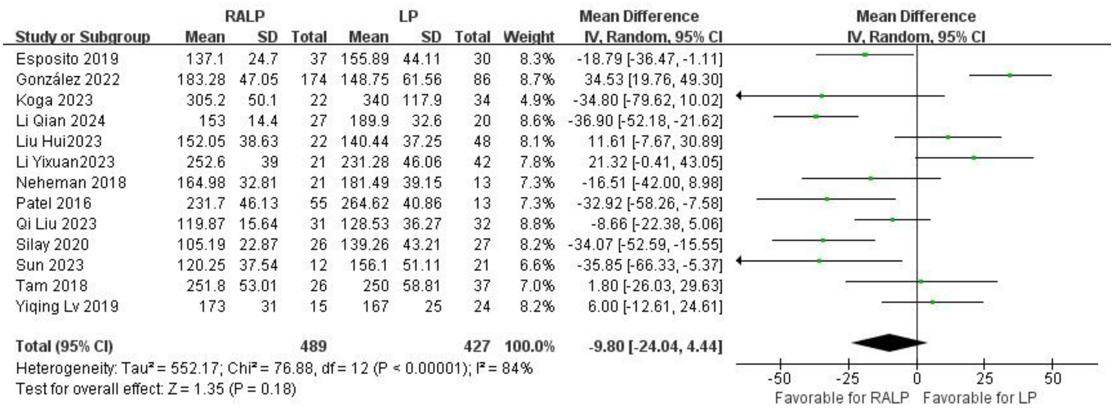

Figure 11 Meta-Analysis of Operative Time for Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.11 Incidence of postoperative complications

Twelve literatures compared the incidence rate of postoperative complications between two surgical methods, heterogeneity test result χ 2 = 3.62, I 2 = 0%, P = 0.98, using fixed effect model. The incidence of complications in the RALP group was lower than that in the LP group, but the difference was not statistically significant [RR = 0.70, 95% CI (0.43, 1.14), P = 0.15] [3-4, 6-10, 12, 14-17] (Figure 12).

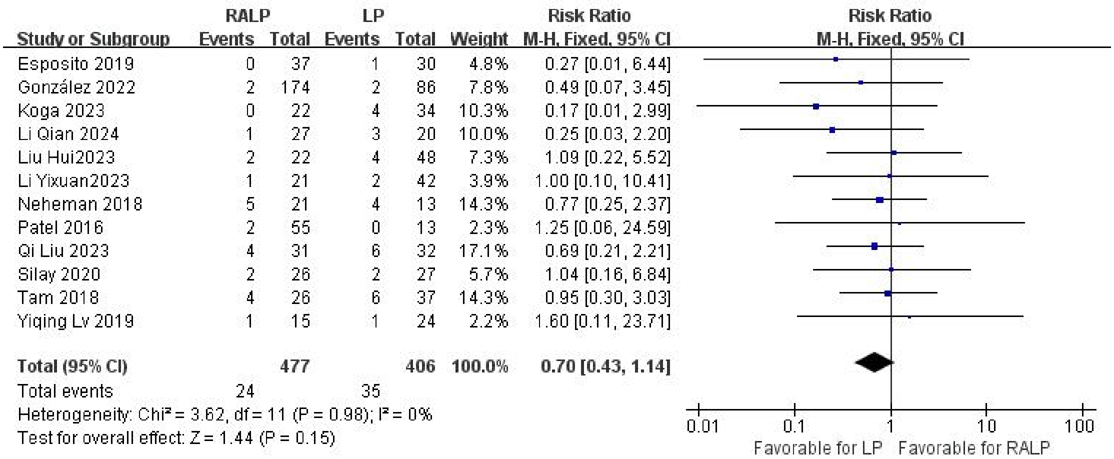

Figure 12 Meta-Analysis of the Incidence of Complications Following Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.12 Follow-up time

Eight literatures compared the follow-up time between two surgical methods, heterogeneity test result $\chi^2 = 53.56$, $I^2 = 87\%$, $P < 0.00001$, using random effect model. There was no statistically significant difference in follow-up time between the RALP group and the LP group [MD = 0.08, 95% CI (-3.33, 3.49), P = 0.96] [3, 8-12, 16, 17] (Figure13).

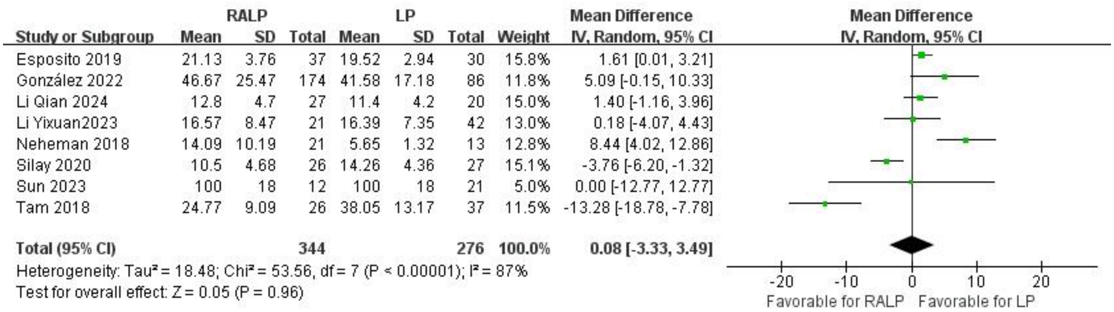

Figure 13 Meta-Analysis of Follow-Up Time for Ureteropelvic Junction Obstruction RALP and LP RALP: Robot-Assisted Laparoscopic Pyeloplasty LP: Conventional Laparoscopic Pyeloplasty

3.3.13 Publication bias

To compare the success rate of RALP and LP, funnel plots were generated and publication bias detection was performed in the included literatures. The graphs were basically symmetrical (Figure 14). However, the development of robotic technology in pediatric surgery is still in its infancy, the number of published studies is not large, and there are few cases involved. There are a large number of randomized prospective studies in the literature, so publication bias is difficult to avoid.

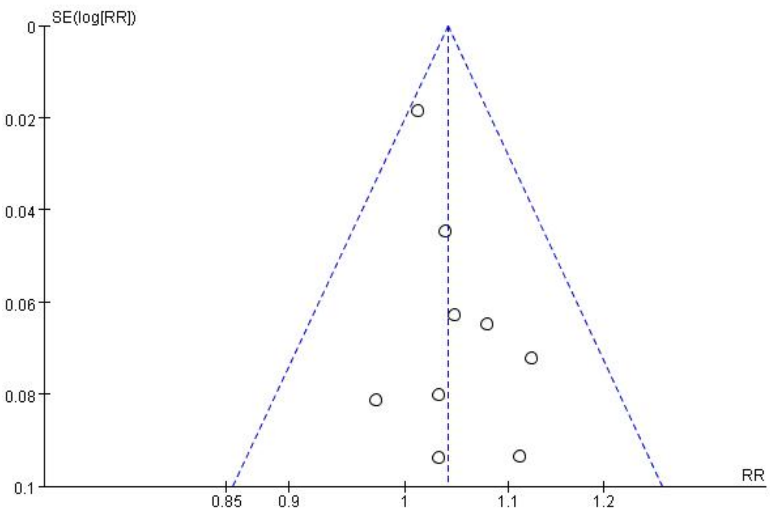

Figure 14 Funnel Plot of Surgical Success Rate of Included Literatures

4 DISCUSSION

Congenital hydronephrosis in children is often caused by ureteropelvic junction obstruction (UPJO) and has many etiologies, which can be divided into: ① ureteropelvic junction stenosis; ② ureteral polyps; ③ high ureteral orifice; ④ ectopic vessels or fibrous cord compression [8]. UPJO is prone to damage renal function, and the main treatment is surgical treatment. The aim of UPJO surgery is to relieve obstruction and improve renal function, and with the development of minimally invasive techniques, laparoscopic pyeloplasty has gradually become a routine procedure for the treatment of UPJO in children [18]. Robotic surgery system has the advantages of high-resolution 3D vision, debulking procedure, highly dexterous robotic arm, short learning curve, etc., overcoming the technical defects of some traditional laparoscopes and has been rapidly developed in the surgical field. Robot-assisted laparoscopic pyeloplasty (RALP) has been used to treat UPJO in children with domestic expert consensus and surgical operation guidelines [1, 19] . At present, several medical centers in China have successively reported the successful application of RALP in pediatric UPJO [20-22] . However, due to cost and surgeon experience, RALP surgery has some limitations in China. The aim of this study was to systematically evaluate the therapeutic effects of traditional laparoscopic pyeloplasty and robot-assisted laparoscopic pyeloplasty for ureteropelvic junction obstruction by meta-analysis.

4.1 Procedural Success

This study showed that the success rate of surgery in the RALP group was higher than that in the LP group. Nine literatures showed that the success rate of operation in RALP group was higher than that in LP group, and the success rate of operation in both groups in each study was greater than 90% [3, 4, 10-15, 17]. Therefore, we believe that both RALP and LP are effective surgical methods for the treatment of UPJO, and with the continuous accumulation of surgeon experience and the continuous development of robotic surgical techniques, the surgical success rate of RALP is generally higher than that of LP group.

4.2 Pyeloureteral Anastomosis Time

This study showed that the ureteropelvic anastomosis time in the RALP group was shorter than that in the LP group. Five of these articles indicated that the ureteropelvic anastomosis time was shorter in the RALP group than in the LP group [3, 7-9, 15]. This is related to the advantages of RALP such as a highly dexterous robotic arm, a high-resolution 3D field of view, and a short learning curve. It suggests that RALP is more sensitive and conducive to intraoperative suture operation, but it is also related to intraoperative experience.

4.3 Intraoperative Blood Loss and Postoperative Drainage Tube Indwelling Time

This study showed that intraoperative blood loss in the RALP group was less than that in the LP group. Five of the articles indicated that the intraoperative blood loss in the RALP group was less than that in the LP group [6-9, 15]. These results indicate that RALP has better visual field and sensitive operation and can better reduce intraoperative bleeding. Among them, 3 literatures showed that the postoperative indwelling time of drainage tube in RALP group was shorter than that in LP group [6, 11, 15]. showed that the RALP group had faster postoperative recovery and less postoperative exudation, which was also related to less intraoperative blood loss. These results indicate that the RALP group is more conducive to rapid recovery.

4.4 Postoperative Hospital Stay and Reoperation Rate

The analysis showed that the length of hospital stay was shorter in the RALP group than in the LP group, indicating that postoperative rehabilitation was faster in the RALP group. However, there are variations in medical regimens across regions that may also influence length of stay. In the table of 9 literatures, the reoperation rate of RALP group was lower than that of LP group, indicating that the success rate and long-term effect of RALP group were better than LP [3-4, 10-15, 17].

4.5 Hospitalization Cost

Four literatures showed that the hospitalization cost of RALP group was higher than that of LP group, which was related to the device cost of robot [6-7, 9, 11] . With the reduction of cost, the development of surgical techniques and the shortening of hospital stay, the hospitalization costs of RALP may be gradually reduced. However, there was no significant difference in operation time between the RALP group and the LP group, which was related to the length of robotic installation and the experience of the surgeon. Postoperative complications mainly included: improper position of double-J tube, flatulence, urinary tract infection, aggravated hydronephrosis, etc. There was no significant difference in postoperative complications between RALP group and LP group. In addition, there was no significant difference between RALP group and LP group in APD value change before and after operation, renal function (GRF) change before and after operation, and postoperative follow-up time. The results showed that there was no significant difference between RALP group and LP group in relieving hydronephrosis and improving renal function.

5 CONCLUSION

In summary, robot-assisted laparoscopic pyeloplasty for ureteropelvic junction obstruction in children has a higher success rate, shorter ureteropelvic anastomosis time, less intraoperative bleeding, shorter postoperative drainage tube indwelling time, lower reoperation rate, and shorter postoperative hospital stay compared with traditional laparoscopic pyeloplasty. showed that RALP had a higher success rate, faster postoperative recovery, and better long-term results. However, due to the high hospitalization costs, there are still some limitations in clinical application.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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IMPROVING IMMO COIL QUALITY VIA SIX SIGMA

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Abstract: This paper takes the Immobilizer antenna (referred to as IMMO) in J Company's keyless entry and start system (Passive Entry and Passive Start, PEPS) as the research object. Using the Six Sigma method, a systematic analysis and improvement were conducted to address the issue of high C/1000 (defects per thousand units) of this component. Through the five stages of Define, Measure, Analyze, Improve, and Control, the key process variables affecting product quality were identified and optimized. The research results show that by improving the winding fixture, optimizing the heating temperature control, and introducing insulation detection between turns, the C/1000 of the IMMO antenna was significantly reduced, thereby improving product quality and customer satisfaction. The research in this paper provides useful references for the quality management of similar products in the automotive electronics industry.
Keywords: Six Sigma; Quality improvement; IMMO; Short circuit detection

1 INTRODUCTION

Quality management assumes a crucial and central position within the manufacturing sector. It functions as the linchpin for ensuring that products adhere to anticipated standards, fulfill customer demands, and fortify the competitiveness of enterprises [1].

PEPS (Passive Entry and Passive Start) system is gradually becoming a main stream option in automotive keyless entry application, which improves the convenience and vehicle anti-theft performance[2]. With the automotive industry experiencing exponential growth, the quality and reliability of automotive electronic products have become subjects of heightened scrutiny[3]. During every phase of automotive component production, spanning from the procurement of raw materials to the final delivery, meticulous supervision and control are not merely advisable but essential to consistently supply products that meet or exceed customer expectations.

Automotive component manufacturers, as suppliers, do not solely concentrate on the quality of the end product. Instead, they also place significant emphasis on identifying and rectifying process defects. For Supplier Quality Engineers (SQEs) working for automotive Original Equipment Manufacturers (OEMs), it is of utmost importance to systematically tackle process quality concerns by implementing the Six Sigma quality improvement methodology. This methodology consists of five sequential and iterative phases: Define, Measure, Analyze, Improve, and Control (DMAIC) [4]. By adopting this approach, it becomes possible to continuously optimize the production processes within the supply chain, thereby minimizing the costs associated with poor quality.

With the extensive application of the Passive Entry Passive Start (PEPS) keyless entry system, automotive key entry has advanced into the intelligent era [5]. The communication between the PEPS controller and the Immobilizer (IMMO) coil is a collaborative procedure that integrates short-range low-frequency wake-up and high-frequency encrypted verification.

The primary scenarios encompass production binding during the vehicle's off-line process, daily vehicle startup by the end-user, and emergency startup situations. The central aim is to allow users to operate the vehicle without the need to physically retrieve the key. Simultaneously, through the encryption mechanism, it effectively deters vehicle theft, thus enhancing the user experience and emerging as a crucial indicator of the competitiveness of contemporary vehicles.

2 PROJECT DESCRIPTION

This article meticulously analyzes the scenario of production halts resulting from IMMO coil failure. Prior to vehicle disassembly, a crucial process is the anti-theft binding of the key to the entire vehicle, known as "key learning"[6]. The system primarily encompasses the PEPS controller (PEPS integration), the IMMO coil along with its wiring harness, the key, and the transponder.

The principal steps are as follows: The assembly plant issues the "key learning" command to the PEPS controller via the diagnostic instrument. Subsequently, the PEPS controller activates the IMMO coil, enabling it to emit a low-frequency signal, typically at 125kHz, of a specific frequency. This signal contains both a wake-up instruction and the vehicle's unique ID. When the pre-bound smart key, which has a built-in transponder, enters the magnetic field of the IMMO coil, the transponder detects the low-frequency signal through its coil and activates the internal circuit. The transponder then transmits its unique ID (the key) to the PEPS controller via high-frequency (433MHz) and receives a response. The PEPS controller verifies the match between the key ID and the vehicle ID. If there are no discrepancies, it binds the two (the relevant information is stored in the encryption chip of the PEPS controller), thereby completing the "anti-theft authentication initialization".

When the vehicle is delivered to the client, in the event that the key has insufficient power, it can be placed in close proximity to the IMMO coil. Through mutual inductive charging between the key and the coil, low-frequency authentication can be achieved. Once the authentication is successful, the vehicle can be started in an emergency.

Nevertheless, Company J discovered during its actual production process that the C/1000 value of the IMMO coil was relatively high. This led to recurrent issues of failed key learning during vehicle disassembly, significantly undermining production efficiency and customer satisfaction. Consequently, undertaking a project to reduce the C/1000 value of the IMMO coil holds substantial practical significance.

3 IMPLEMENTATION OF SIX SIGMA

To the successful execution of the Six Sigma project greatly contributed the belief and support of top-management and the active involvement of team members [7]. As a systematic problem-solving tool, the core concept of Six Sigma is to be data-driven, using structured processes and statistical analysis methods to identify and eliminate negative factors affecting target indicators, thereby achieving operational performance improvement. In practical application, DMAIC (Define - Measure - Analyze - Improve - Control) is the most common and widely used implementation framework, applicable to quality improvement projects in various fields such as manufacturing and services. This paper takes the IMMO coil C/1000 reduction project as a case to explore its standardized implementation process, aiming to provide a reference operational model for quality improvement in the automotive parts industry.

3.1 Project Objectives and Implementation Plan

In May 2023, the SUV production line experienced a failure where vehicles could not be associated with car keys. The fault code was "B102049 09 immo coil failure". After swapping the ABA components, the fault was traced to the IMMO coil. Based on the analysis of fault data, the monthly C/1000 (number of faults per 1,000 units) reached 1.94. The team decided to reduce the C/1000 of the IMMO coil incoming material from 1.94 to 0.1, extending the challenging target to 0.05. The team formulated the project plan following the Six Sigma DMAIC (Define-Measure-Analyze-Improve-Control) methodology, as shown in Table 1.

Table 1 Project Schedule (Gantt Chart)

Project Tasks		D: 2023-07-20						M: 2023-08-22					A: 2023-09-27				I:2023-10-31				C: 2023-11-29				
		June				July				August				September				October				November			
Phase	Tasks	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W	1W	2W	3W	4W
D	Problem statement	■																							
	Process flowchart		■																						
	Determine the CTQs			■	■																				
	Define the goals					■																			
	Project Approval						■																		
M	Defining measurement methods							■																	
	Determine the data type								■																
	Data collection plan									■															
	Conduct MSA										■														
	Assessment of process capability											■													
A	Review Analysis Methods												■												
	Select an analysis tool													■											
	Apply graphic analysis tools														■										
	Identify changes															■									
I	Choose the improvement plan																■								
	Conduct failure mode analysis																■								
	Conduct a cost-benefit analysis																	■							
	Small-scale trial production																		■						
	Verify improvement																			■	■				
C	Develop control strategy																					■			
	Prepare the control plan																						■		
	Update the operation procedures																							■	■

3.2 Define (Definition Phase): Define the Problem and the Objective

During the key-offline learning process at the assembly plant, the IMMO coil communicates with the key using a 125kHz low-frequency signal. In case of occasional failures, the learning process fails due to inability to resonate, and the vehicle cannot learn the key. The failure rate is 1.94 C/1000, and the performance is deteriorating. See Figure 1 for the trend chart of the problem. The IMMO coil's drawing specifies the inductance value specification as 162 ± 2% μH @ 125kHz. The measured value of the faulty part is 19.20 μH, indicating a low inductance. This coil is from a certain manufacturer. Therefore, the research scope of the project is the supplier's production process.

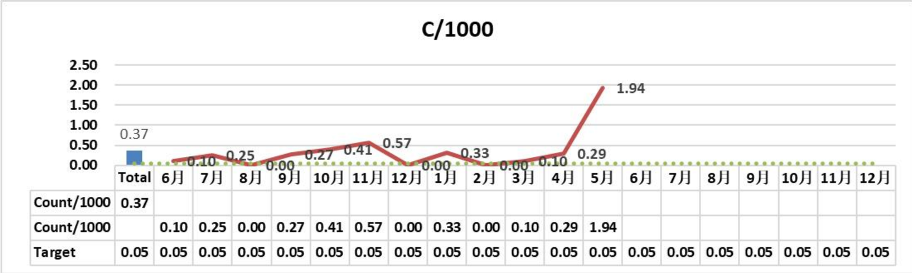


Figure 1 Trend Chart of the Problem

At the supplier's site, using the LCR measuring instrument (1V, 125kHz), the problem points were identified one by one: the insulation layer was damaged in the two outermost turns of the coil from the edge of the housing. The location of the injury is shown in Figure 2.

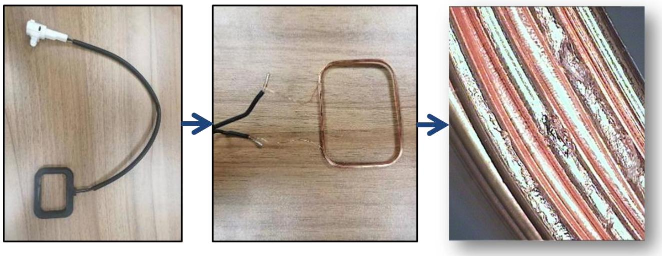


Figure 2 Location of the Injury

3.3 Measurement Phase: Quantification of Current Process Status

The core task of the measurement stage is to establish a measurement system for the suspected factors, collect data, and evaluate process capability.

Firstly, review the existing process flow, such as "incoming material inspection → winding → assembly and foot welding → injection molding → low-pressure injection molding → final product inspection", and identify the key processes with high impact. Use the SIPOC tool to analyze the influencing factors of each key process of the coil. The fishbone diagram aids in organizing complex information and offers a structured approach to decision-making and actual planning of maintenance interventions[8]. Figure 3 is Using the fishbone diagram to brainstorm and list the factors with high impact.

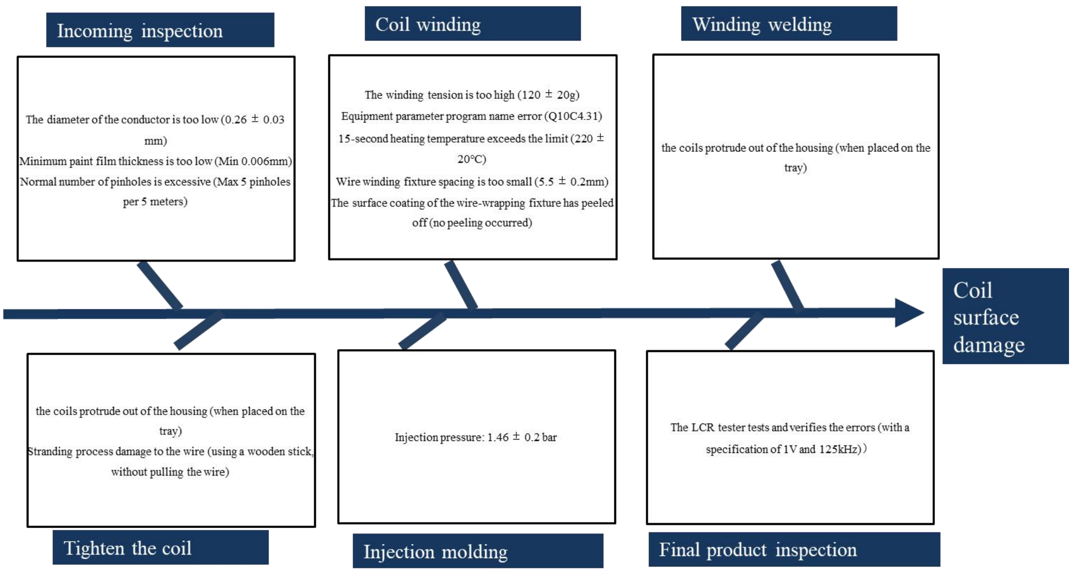


Figure 3 Fishbone Diagram

Then, the causal matrix table is used to evaluate the weight of each input variable on the defect. By analyzing the influence degree of each input parameter on the coil surface, seven key factors are determined: 1. Excessive winding tension, equipment program error, line damage, fixture coating off, low film thickness, too many pinholes, and LCR tester test error. Combined with the results of on-site production evidence investigation, as shown in Table 2, the remaining three impact factors after screening have insufficient evidence, and the three impact factors are in poor state, all of which need further study on process capability performance.

Table 2 Identify Key Factors

No	process	factor	evidence	stat
1	Incoming inspection	The diameter of the conductor is too low (0.26 ± 0.03 mm)	Incoming Material Inspection Report	A
2		Minimum paint film thickness is too low (Min 0.006mm)	Incoming Material Inspection Report	A
3		Normal number of pinholes is excessive (Max 5 pinholes per 5 m	Incoming Material Inspection Report	A
4	Coil winding	The winding tension is too high (120 ± 20g)	Initial inspection of the production line, unsure of the fluctuations during the production process	B
5		Equipment parameter program name error (Q10C4.31)	Daily inspection record form, OK.	A
6		15-second heating temperature exceeds the limit (220 ± 20℃)	Initial inspection before starting production - unsure about the fluctuations during the production process	B
7		Wire winding fixture spacing is too small (5.5 ± 0.2mm)	Not actually measured	B
8		The surface coating of the wire-wrapping fixture has peeled off (n	The surface of the fixture is worn, but the extent of the damage is uncertain.	C
9	Tighten the coil	the coils protrude out of the housing (when placed on the tray)	Forming material tray, after transfer, there is no risk of material spilling out of the shell.	A
10		Stranding process damage to the wire (using a wooden stick, with	After inspecting the materials, conduct a magnifying glass examination to ensure there are no damages.	A
11	Injection molding	Injection pressure: 1.46 ± 0.2 bar	Real-time equipment monitoring shows no abnormalities in the production inspection record sheet.	A
12	Final product inspection	The LCR tester tests and verifies the errors (with a specification o	There is an NTF item, and the re-mounting function is not qualified.	C

Process Elements	
Element OK	A
Investigating	B
Element Not Capable	C
Element Removed	D

Before the process capability analysis, it is necessary to ensure the reliability of the measurement system, that is, to formulate sampling plans for key processes (winding, inspection), and analyze the measurement system. The summary results are shown in Table 3.

Table 3 Measurement System Analysis Results

No.	Key Factor	Item	Data Type	Sample size	Frequency	Tool	Result	Date
1	X1:The winding tension is too high (120 ± 20g)	winding tension	Variable data	30	2 times/day	Tension meter	Gage R&R< 10%; NDC>5, acceptable	2023.8
2	X2:15-second heating temperature exceeds the limit (220 ± 20°C)	heating temperature	Variable data	10	2 times/day	Temperature meter	Gage R&R< 10%; NDC>5, acceptable	2023.8
3	X3:Wire winding fixture spacing is too small (5.5 ± 0.2mm)	Wire winding fixture spacing	Variable data	10	2 times/day	Vernier caliper	Gage R&R< 10%; NDC>5, acceptable	2023.8
4	X4:The surface coating of the wire-wrapping fixture has peeled off	fixture has peeled off	Attribute data	10	2 times/day	Visual inspection	Kappa value > 0.8, acceptable	2023.8
5	X5:LCR tests and verifies the errors (with a specification of 1V and 125kHz))	LCR tester test error	Attribute data	300	Continuous	High-voltage tester	Kappa value < 0.8, unacceptable	2023.8

Among them, in the LCR tester process, 30 measurement objects were prepared (20 coils with varying degrees of damage and 10 good coils), and two operators conducted repeated measurements twice, with a total of 120 tests. The misjudgment rate of the equipment for faulty parts was 47% (NG judged as OK), and the Kappa value was less than 0.8, making the measurement system unacceptable, as shown in Figure 4. The primary measure for fault analysis is to protect the customer, and it is urgent to implement a new detection method for the current situation. After benchmarking with the same industry, an additional high-voltage test was added, using a 2900V high-voltage tester (based on 70% of the 4200V insulation voltage of the enameled wire) to detect energy loss. The MSA verification Kappa value was greater than 0.8, which was acceptable.

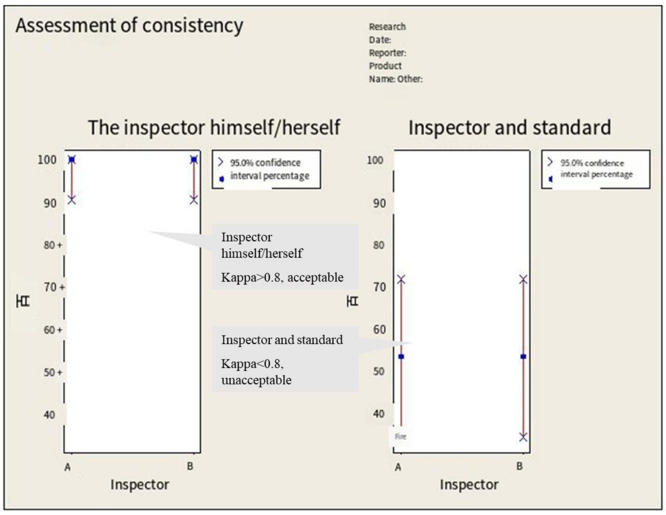


Figure 4 Assessment of Consistency

Based on a qualified measurement system, process capability analysis was conducted. According to the target of CPK >

1.33 and DPMO less than 3.4, it was found through investigation and analysis that the surface coating of the winding fixture was peeling off， as table 4 shows.

Table 4 Process Capability Analysis Results

No.	Key Factor	Item	Data Type	Sample size	Frequency	Tool	data presentation	Result
1	X1:The winding tension is too high (120 ± 20g)	winding tension	Variable data	30	2 times/day	Tension meter	CPK=2.23	acceptable
2	X2:15-second heating temperature exceeds the limit (220 ± 20℃)	heating temperature	Variable data	10	2 times/day	Temperature meter	CPK=1.35	acceptable
3	X3:Wire winding fixture spacing is too small (5.5 ± 0.2mm)	Wire winding fixture spacing	Variable data	10	2 times/day	Vernier caliper	CPK=1.44	acceptable
4	X4:The surface coating of the wire-wrapping fixture has peeled off	fixture has peeled off	Attribute data	10	2 times/day	Visual inspection	The surface Teflon coating has peeled off, exposing the base material / twice	unacceptable
5	X5:LCR tests and verifies the errors (with a specification of 1V and 125kHz)）	LCR tester test error	Attribute data	300	Continuous	High-voltage tester	DPMO=20000	unacceptabl

3.4 Analyze (Analysis Stage): Identify the Root Cause

After checking the surface coating of the winding fixture, it can be clearly seen that there is wear at the contact position of the coil. The outermost anti-wear layer of the fixture has been scratched. And touch by hand, can obviously feel the position of the contact coil is rough and not smooth. The high voltage tester (2900V) was used to continue to check the bare coil. The coil produced by the fixture was 3170 PCS, and the faulty parts with insufficient voltage tolerance were 6 PCS. Observe its air discharge position, which is located in the left and right section of the coil in Figure 5 below, which is exactly the contact surface between the coil and the fixture.

Further process confirmation is carried out to confirm that the surface coating of the winding fixture has not been regularly inspected since it was put into use in 2021, there is no relevant maintenance requirements, and there is no life management.

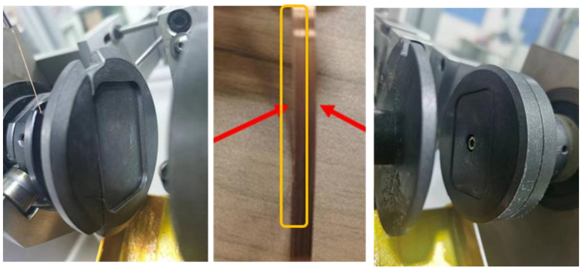


Figure 5 The Coil Damage Point and the Fixture Position Correspond

3.5 Improve: Implement the Optimization Plan

Regarding the problem of the wire clamping fixture falling off, a new fixture was immediately customized. The produced coils with the new fixture were analyzed for data. The reliability of the fixture was verified by analyzing the change in the defect rate. This fixture was identified as a spare part for the winding machine equipment. A maintenance plan was formulated, and a replacement frequency was determined. The coating condition of the production coils was confirmed daily at the start of each shift. Additional spare parts were added, and the production clamps were required to be replaced compulsorily every 6 months and re-coated at the factory. Other devices in contact with the enameled wire, such as the lead-out pins, felt pads, and idler pulleys, were expanded laterally to increase protection and maintenance.

Although the team has been using high-voltage testers as recommended by the industry to supplement the measurement of inter-turn micro-short circuits in the coils, for the winding density of this coil, it is still worth the team to continue to increase the sample size for research on how much test voltage to use. The research method is as follows: Take 20 faulty pieces and conduct 50 tests each at 500V, 1000V, 2000V, and 2500V. The experimental results are shown in Table 5. The experiment indicates that a 100% result repeatability can be achieved at 2500V. Based on industry experience, the detection voltage is set at 70% of the conductor's rated voltage. The IMMO coil enameled wire withstands a voltage of 4200V. The final test voltage is set at 2900V and updated in the PFMEA and control plan.

Table 5 High-voltage Test Results under Different Measurement Voltages

Voltage (V)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20
500	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1000	10%	4%	4%	2%	4%	0%	0%	2%	6%	4%	0%	0%	8%	6%	0%	2%	4%	6%	2%	2%
2000	100%	92%	82%	76%	78%	88%	86%	92%	100%	92%	86%	84%	86%	82%	72%	76%	78%	82%	100%	100%
2500	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

By adding clamping accessories and re-coating the surface, a high-pressure energy loss test was conducted on the coils before and after the repair of the original coating of the clamping fixtures. The inventory pieces produced by the fixtures with the original coating that had fallen off were re-examined, and 11,018 pieces were re-examined, with 20 NG (non-conforming) items detected. After replacing with new coated fixtures, 6,000 pieces were produced, and 1 NG item was detected.
Based on the above test data, using the two-ratio hypothesis test, it was confirmed whether the defect rate of the coils produced after the fixture coating repair decreased.
▪ Sample 1: Coils before fixture coating repair
▪ Sample 2: Coils produced after using the new fixture
▪ H0: P1 = P2, the test defect rate before and after fixture replacement is consistent
▪ Two-ratio test: As shown in Figure 6, P < 0.05, Reject H0, there is a difference between the two states.
▪ The current sample size is sufficient to meet the efficacy requirements.
Conclusion: After replacing the fixtures, there is a significant improvement.

Two-ratio test and confidence interval

sample	X	N	sample p
1	20	11018	0.001815
2	1	6000	0.000167

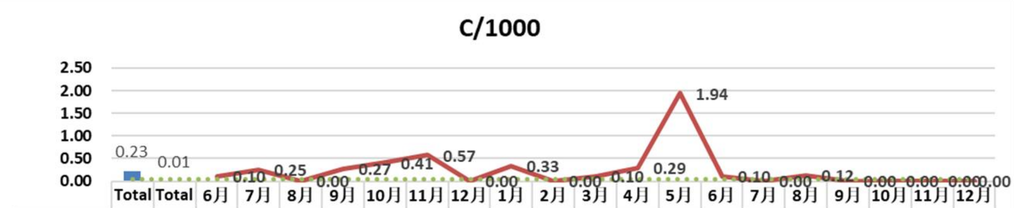
P<0.05, Reject the null hypothesis

Gap = p (1) - p (2)
Gap estimation : 0.00164854
The 95% confidence interval for the gap: (0.000789231, 0.00250786)
Test for the gap being equal to 0 (versus not equal to 0): Z = 3.76 P-value = 0.000
Fisher's exact test: P-value = 0.002
Note * The normal approximation for small samples may not be accurate.

Figure 6 Two-ratio Hypothesis Test

With the newly produced modified components, the failure rate during loading has dropped to nearly 0, showing a significant improvement. The trend of failure data is shown in Table 6.

Table 6 Trend of C/1000



	Total	Total	6月	7月	8月	9月	10月	11月	12月	1月	2月	3月	4月	5月	6月	7月	8月	9月	10月	11月	12月
Count/1000	0.23	0.01																			
Count/1000			0.10	0.25	0.00	0.27	0.41	0.57	0.00	0.33	0.00	0.10	0.29	1.94	0.10	0.00	0.12	0.00	0.00	0.00	0.00
Target	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

3.6 Control (Control Phase): Solidify the Improvement Achievements

Based on the core achievement of significantly reducing the IMMO coil C/1000 by this project, great emphasis was placed on the long-term implementation and experience accumulation of improvement measures. Through systematic document upgrades and the establishment of platform-based preventive mechanisms, the sustainable implementation of quality improvement results was ensured.
At the level of document system updates, all key documents of the entire process have been revised and verified:
▪ PFMEA (Process Potential Failure Mode and Effects Analysis) has added failure mode analyses such as "inter-turn short circuit of the coil" and "coating detachment of the fixture causing insulation damage", supplemented with potential risk points such as failure of high-voltage tests and abnormal stray capacitance, clearly specifying preventive control measures for factors such as fluctuation in winding tension and unstable heating temperature, reducing the RPN (Risk Priority Number) from the high-risk range before improvement to below the industry benchmark value, and forming a risk early warning model covering the entire chain of design, production, and inspection.

▪ The control plan (CP) has focused on strengthening the monitoring requirements for key process parameters, such as increasing the inspection frequency of the coating status of the winding fixture from "monthly" to "mandatory inspection at the start of each shift", adding 2900V voltage calibration records for the high-voltage tester (once per shift), clearly defining the dual-criterion standards for inductance value and energy loss rate (inductance 162±2% μH@125kHz and energy loss ≤ 5%), and uploading test data to the MES system for real-time traceability to achieve a closed-loop.
▪ Standard operation procedures (SOP) have refined operational norms, including the debugging steps of the winding machine tensioner, safety precautions during high-voltage tests, and the first-piece verification process after fixture replacement, with accompanying graphic and textual operation diagrams to ensure that front-line employees can directly refer to and execute, reducing human operational deviations.
▪ In terms of experience accumulation and platform-based prevention, the project team has incorporated the "fault mode - root cause - control measure" experience library formed by this improvement into the enterprise sharing platform:
▪ Through enterprise knowledge base updates, subsequent new projects can call upon the risk data in this FMEA during the design stage, avoiding similar issues such as inter-turn short circuit and failure of detection methods in advance, achieving the preventive effect of "one improvement, multiple benefits".
After cross-departmental joint review and confirmation, these documents have been released and come into effect. The consistency of on-site execution is 100%, and the process capability monitoring for 3 consecutive months shows that the IMMO coil C/1000 is stably controlled below 0.05, verifying the effectiveness of the solidification measures, and accumulating replicable practical experience for the standardization and platformization of enterprise quality improvement.

4 CONCLUSION

The IMMO coil C/1000 reduction project, using the DMAIC methodology as the framework, through precise problem definition, scientific process measurement, in-depth root cause analysis, efficient implementation of improvements, and strict control implementation, not only did IMMO coil C/1000 achieve a breakthrough improvement from 1.94 to below 0.05, but also established a replicable quality improvement system. The upgrade of the entire process documents from PFMEA, control plans to SOPs transformed scattered improvement experiences into standardized management norms; while the platform-based accumulation of the "failure mode - prevention measures" experience database broke the boundaries of a single project and provided forward-looking preventive ideas for the quality control of similar products and even across different fields. The closed-loop implementation of the project not only verified the practical value of Six Sigma in manufacturing quality improvement, but also demonstrated the profound significance of the "data-driven, systematic policy, and continuous accumulation" quality concept in enhancing enterprise competitiveness, laying a solid foundation for subsequent high-quality development.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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THE FUTURE DEVELOPMENT OF NEW ENERGY VEHICLES AND KEY COMPONENTS

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Abstract: Driven by policies worldwide, new energy vehicles (NEVs) have developed rapidly in recent years, with their market share increasing annually. By analyzing the current status of NEVs at home and abroad, this paper sorts out the technologies and development directions of NEVs and their key components. From the perspective of sustainable development of NEVs, it further analyzes these core technologies, summarizes future technical routes, and promotes the healthy development of NEVs.
Keywords: New energy vehicles; Key components; Future development

1 INTRODUCTION

Against the backdrop of the accelerated transformation of the global energy structure and the in-depth advancement of the "dual-carbon" goals, the new energy vehicle industry has shifted from policy-driven growth to an explosive development phase driven by both market and technology. In 2024, the penetration rate of new energy vehicles in China exceeded 50%, and their global sales accounted for over 60% of the total, marking that new energy vehicles have officially become the dominant force in the automotive market. However, behind this progress, the industry is facing multiple challenges such as technological iteration and vehicle safety. As the core support of new energy vehicles, key components' technological breakthroughs and industrial collaboration capabilities will directly determine whether China can continue to lead in the global new energy race. Therefore, it is necessary to build a globally competitive new energy industry ecosystem and provide Chinese solutions for global energy transformation and sustainable development.

2 CURRENT STATUS OF NEW ENERGY VEHICLES AT HOME AND ABROAD

In recent years, driven by factors such as stricter environmental protection requirements and energy structure transformation, the development of NEVs has accelerated. Although the development status varies across countries, the market share of NEVs has generally increased year by year.

In 2024, China's automobile production and sales reached 31.282 million and 31.436 million units, respectively, with year-on-year growth of 3.7% and 4.5%. Among them, NEV production and sales reached 12.888 million and 12.866 million units, up 34.4% and 35.5% year-on-year, accounting for 40.9% of total new car sales, an increase of 9.3 percentage points compared with 2023[1]. From January to May 2025, China's NEV production and sales reached 5.699 million and 5.608 million units, up 45.2% and 44% year-on-year, accounting for 44% of total new car sales[2].

Globally, in 2024, global electric vehicle sales reached 17 million units, a year-on-year increase of about 25%, accounting for more than 20% of the global automobile market for the first time; in the first quarter of 2025, global electric vehicle sales grew 35% year-on-year[3].

The above data show that NEVs are developing vigorously at home and abroad. Driven by national policies, NEV consumption has grown steadily, promoting the further extension and improvement of the NEV industry chain, which in turn helps expand the NEV consumer market.

3 SORTING OUT TECHNOLOGIES OF NEW ENERGY VEHICLES AND KEY COMPONENTS

NEVs are generally classified into three categories: Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs/PHEVs), and Fuel Cell Electric Vehicles (FCEVs). Regardless of the category, they all revolve around the "three electric systems" (battery, motor, and electronic control), supplemented by key technologies such as intelligence and connectivity, and lightweighting.

3.1 Battery Technology

Current NEV batteries mainly use lithium-ion batteries, including ternary lithium and lithium iron phosphate technologies. Core indicators for evaluating batteries include energy density, charging speed, safety, and cost.

3.2 Motor Technology

NEV drive motors convert electrical energy from batteries into kinetic energy for vehicle operation. Common drive motors include DC motors, asynchronous motors, and permanent magnet synchronous motors. Core evaluation indicators are power density, efficiency, noise, and reliability.

3.3 Electronic Control Technology

The NEV electronic control system manages motor operation, directly affecting key performance indicators such as maximum speed and acceleration. It also handles complex tasks like energy recovery to ensure efficient and safe vehicle operation. Core indicators include energy management efficiency, smoothness of driving mode switching, and safety redundancy.

3.4 Intelligence and Connectivity Technology

Intelligent and connected vehicles integrate advanced on-board sensors, controllers, actuators, and modern communication/network technologies to enable intelligent information exchange and sharing between vehicles, humans, roads, and backends. This enhances safety, energy efficiency, and environmental performance, ultimately enabling autonomous driving. The core evaluation indicator is safety, including the safety of traffic participants and data security.

3.5 Lightweight Technology

NEVs are generally heavier due to onboard batteries. To reduce energy consumption and mitigate pedestrian impact risks, various lightweight technologies are widely adopted, such as extensive use of aluminum alloys and integrated die-casting. Core indicators include weight reduction ratio, cost, and process feasibility.

4 DEVELOPMENT DIRECTIONS OF NEV AND KEY COMPONENT TECHNOLOGIES

Based on the above analysis, the following sections outline future technology trends.

4.1 Battery Technology Development

Current battery challenges include slow charging, insufficient range, and heavy weight. Future development will focus on addressing these issues.

4.1.1 Improving charging speed

To solve slow charging, NEV manufacturers are developing high-power charging technologies. For example, BYD launched its "Megawatt Charging" technology in March 2025, achieving a global mass-produced maximum charging power of 1 megawatt (1000kW), marking the entry into the "megawatt era"[4]. This technology enables 2 km of range per second and 400 km of range with 5 minutes of charging, with a single-module motor power of 580kW, demonstrating breakthroughs in solving charging speed pain points.

4.1.2 Enhancing battery range

Battery capacity is primarily influenced by energy density. Efforts are underway to develop high-energy-density lithium-ion batteries, with silicon-carbon anodes and high-nickel cathodes enabling energy densities of 280-300Wh/kg, supporting ranges over 600 km. Solid-state batteries are another promising solution, with theoretical energy densities of 400-500Wh/kg and cycle life exceeding 3,000 times[5].

4.1.3 Battery lightweight technology

Battery lightweighting focuses on battery pack casing materials, processing, and design. For example, Baumeister used aluminum foam composite sandwiches to produce a 20kWh battery pack lower casing, reducing weight by 10-20%[6]. Choi used nylon 6 (PA6) as a matrix with carbon and glass fibers (total fiber content ≤40%) to reduce casing weight[7]. Mao Zhanwen collaborated with FAW to develop a carbon fiber battery pack casing, reducing weight from 110kg to 19kg[8]. Shao Mingding used glass fiber-reinforced composites (glass fiber woven fabric with epoxy vinyl ester resin) via prepreg compression molding for lightweight battery casings[9]. Welding technology also plays a crucial role in lightweight battery pack manufacturing; optimized welding methods and precision processes reduce weight while improving energy/power density[10]. Tesla's Model 3 uses an optimized crash-resistant design to transfer impact loads and innovatively adopts a shallow tray-shaped aluminum plate for the battery pack lower casing, reducing the 80.5kWh battery pack weight to only 478kg[11].

4.2 Motor Technology Development

Permanent magnet synchronous motors currently dominate, with power densities exceeding 4kW/kg and efficiency reaching 97%. Oil-cooling technology increases continuous torque output by 20%. In-wheel motors are also advancing rapidly, using mature distributed drive technology for four-wheel independent control (e.g, lateral movement and crab walking modes), but their cost is twice that of traditional motors, making cost reduction a key focus[12]. Hairpin motors use flat wire windings to increase winding density, improving power density. This reduces motor size, lowers DC resistance, enhances heat dissipation, and extends range[13].

4.3 Electronic Control Technology Development

Electronic control technology is evolving in multiple directions. Rule-based energy management strategies for hybrid vehicles reduce equivalent fuel consumption by 10% compared to traditional vehicles[14]. X-by-wire chassis technology is another major trend, providing a physical platform for software-based functional and performance upgrades, essential for vehicles to become mobile intelligent terminals. BYD's Yangwang U8 uses the "Yi Sifang" platform with four-motor distributed drive for extreme stability and agile steering; Huawei's Turing intelligent chassis integrates drive, braking, and suspension control to enhance vehicle motion capabilities[15].

4.4 Intelligence and Connectivity Development

Intelligent connected vehicles represent the deep integration of the automotive industry with AI and big data, driven by technological innovation, policy support, and an improving industrial chain[16]. The core direction is autonomous driving, building a "vehicle-road-cloud" integrated connectivity system based on 5G or faster networks to create safer and more efficient intelligent transportation.

4.5 Lightweight Technology Development

NEVs are heavier than traditional fuel vehicles due to batteries, making weight reduction a key challenge for manufacturers. Current efforts focus on materials and processes. Body structures using aluminum alloys or carbon fiber-reinforced composites achieve over 30% weight reduction compared to traditional steel bodies; chassis components using aluminum or magnesium alloys reduce weight by over 20%[17]. Integrated aluminum alloy die-casting for vehicle bodies is a recent lightweight hotspot. Compared to traditional steel stamping-welding bodies, large die-casting machines produce integrated bodies in one step, reducing manufacturing processes, improving efficiency, and achieving 5-8% weight reduction[18].

5 ANALYSIS OF CORE TECHNOLOGIES FOR SUSTAINABLE NEV DEVELOPMENT

A deep understanding of NEV technologies highlights the need to leverage NEVs' advantages and address weaknesses for sustainability. Key focus areas include lightweighting (battery and vehicle), solid-state batteries, autonomous driving, and data security.

5.1 Lightweight Technology

Weight reduction is critical to overcoming NEV weaknesses. Reducing weight enhances range, lowers energy consumption and carbon emissions, optimizes performance, cuts costs, and drives technological innovation and industrial upgrading. This "multi-win" choice (technical, economic, environmental, and user experience) is revolutionary, promoting advancements in materials science, manufacturing processes, and design, supporting the industry's move toward high-end and intelligent development.

5.2 Solid-State Battery Technology

Solid-state batteries significantly address range anxiety, charging time, lifespan, and safety issues in NEVs, especially BEVs. As a core next-generation battery technology, they use non-flammable solid electrolytes (e.g., oxides, sulfides, polymers) to eliminate thermal runaway risks. High energy density reduces battery pack size and weight, improves handling, lowers per-kilometer costs, and promote electric vehicles to move toward "price parity with fuel-powered vehicles" and even lower costs.

5.3 Autonomous Driving Technology

Autonomous driving transforms transportation and profoundly impacts social efficiency, safety, economic structures, and lifestyles. Integrating AI, sensors, communications, and automotive engineering, it enhances travel experience, frees hands, improves traffic safety by reducing human error, optimizes traffic flow, and drives trillion-level market growth, reshaping the automotive industry.

5.4 Data Security

Increasing vehicle intelligence and connectivity generates massive data, critical to privacy protection, traffic stability, and national security. Personal data (e.g., trajectories, in-vehicle images, voice interactions, payment info) risks exposure, fraud, or misuse if compromised. In terms of social transportation, if the linkage between the internet of vehicles, intelligent traffic signals, and road sensors is maliciously interfered with, it may cause large-scale congestion or accidents. High-definition cameras and precision positioning in connected vehicles could threaten national security if exploited for mapping or military target identification. Ensuring data security is therefore paramount for NEV development.

Sustainable development requires high-quality, healthy, and safe progress. Only by meeting these standards can China's NEVs and key components gain a global competitive edge.

6 CONCLUSION

Driven by "dual carbon" goals, NEV development is inevitable but faces significant challenges. Thanks to the efforts of Chinese automotive professionals and effective policy guidance, progress is being made. NEV usage environments have improved, with better infrastructure and enhanced user convenience. There is reason to believe in the sustainable development of China's NEV industry.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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CROP PLANTING STRATEGY BASED ON DYNAMIC PLANTING SCHEME OPTIMIZATION MODEL

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Abstract: As a key agricultural region in China, the development of organic farming in North China has a profound impact on promoting sustainable rural economic growth, enhancing farmers 'quality of life, and advancing the construction of beautiful villages. This paper focuses on the application of dynamic programming models for the utilization strategies of arable land resources in the organic farming industry in North China. By using dynamic programming models, it provides tailored solutions to the specific conditions of rural areas, considering factors such as time, resources, and costs, to develop planting strategies that achieve optimal results under various conditions. During the model construction process, the climate characteristics of North China and the special requirements of organic farming are fully considered. Monte Carlo simulation algorithms are used for iterative screening, followed by adjustments based on elastic demand theory to select the best planting strategy. The application of this dynamic programming model not only enhances the production efficiency of organic farming but also reduces planting risks due to changes in climate and market conditions. It also promotes the rational allocation and efficient use of agricultural resources. By optimizing the utilization strategies of arable land resources, it lays a solid foundation for the sustainable development of the organic farming industry in North China's rural areas, contributing to the goals of rural revitalization and the construction of beautiful villages.
Keywords: Cultivated land resources; Organic farming; Dynamic planning; Sustainable development

1 INTRODUCTION

As China's rural revitalization strategy advances, the 'Comprehensive Rural Revitalization Plan (2024-2027)' emphasizes measures to boost farmers' income, accelerate agricultural and rural modernization, and promote comprehensive upgrades in agriculture, progress in rural areas, and all-around development of farmers. In the process of exploring sustainable development, rural areas are increasingly focusing on the rational allocation and efficient use of land resources. Organic farming, a key direction in modern agriculture, not only enhances the quality of agricultural products but also maintains soil health through ecological practices, promoting sustainable agricultural development. However, selecting suitable crop varieties and optimizing planting strategies based on local climate and soil conditions is crucial for the effective utilization of rural land resources and sustainable development.
The village under discussion is situated in North China, a typical cool region. The area has distinct climatic features, with consistently low temperatures throughout the year, which results in most farmlands being suitable for only one crop per year. This climate not only limits the growth cycle of crops but also introduces uncertainty into farmers' income. Selecting the right crops to plant within the limited growing season is crucial for optimizing planting strategies and enhancing agricultural productivity.
Studies on cultivated land use cover security dynamics, contradiction analysis, and efficiency evaluation. Huang et al. analyzed Hubei's cultivated land security, finding overall improvement 2010-2019 with declining quantity security and "west-high-east-low" spatial pattern [1]. Li et al. revealed a poverty contradiction in Heilongjiang's arable-rich regions, highlighting the importance of quality and location [2]. Zhu et al. proposed balancing economy and land protection in Huang-Huai-Hai Plain to reduce environmental pressure [3]. Zhang et al. found rising utilization efficiency in Henan 2000-2020, driven by population and economy [4]. Bogale et al. analyzed Ethiopian land use change, noting the need for policies to address farmland expansion and forest planting conflicts [5]. However, existing studies focus on single regions or dimensions, lacking cross-system dynamic synergy analysis.
Organic farming research focuses on system synergy and technological innovation. Csambalik et al. compared organic farming and plant factories, emphasizing regulatory and medium optimization [6]. Javed et al. noted that actinomycetes promote soil organic matter cycling via enzymatic reactions [7]. Hafez et al. confirmed that the combined use of spent grain and azospirillum improves soil fertility better than chemical fertilizers [8]. Nath et al. proposed lignin-derived carbon materials for pollutant degradation, aiding environmental remediation [9]. Sani et al. highlighted biostimulant synergy in enhancing organic crop yield and stress resistance [10]. However, few studies integrate the synergy of microorganisms, materials, and policies, with insufficient region-specific strategies.
The innovation of this paper lies in constructing a dynamic programming model that integrates "quantity-quality-ecology-economy" constraints of cultivated land, combining North China's climatic characteristics and organic farming technologies to achieve spatio-temporal optimization and dynamic risk control for cultivated land use in organic farming. As a multi-stage decision optimization method, dynamic programming has demonstrated remarkable problem-solving capabilities in various fields in recent years. Such models excel in their ability to integrate multiple factors

within rural organic farming, including soil quality, crop varieties, market demand, and environmental constraints—an integration that is crucial for formulating optimal strategies for arable land utilization in organic agriculture.

2 MODEL

2.1 Dynamic Programming Model

Located in the north of the mountainous area, the temperature is low all year round, and most farmland can only grow o ne crop per year. Let the crop number be *i*, and the name of the planting plot or greenhouse be *j*, $i=\{1,2,3,\ldots,a\}$, $j=\{1,2,3,\ldots,b\}$, $a=41$, $b=54$, the plots were numbered and divided into four types [G1, G2, G3, G4]. If the year is *k* an d some cultivated land can plant two seasons of crops per year, then a certain plot of land can be planted with m seasons of crops per year, where i_a is the crop planted in the first season and i_b is the crop planted in the second season. The nu mber of planting seasons per year for different types of land parcels, i.e. *j* and *m*, satisfies the relationship:

$$\begin{cases} m=1, & j\in G_1 \\ m=1\ or\ 2, & j\in G_2 \\ m=2, & j\in G_3\cup G_4 \end{cases} \tag{1}$$

The total planting area of the i-th crop in the k-th year is X (k), and S. is the total cultivated land area. If the area of the i-th crop planted on the j-th plot in the k-th year is x (k), then there is.

$$\sum_{i=1}^{a}\sum_{j=1}^{b}x_{ij}(k)=\sum_{i=1}^{a}X_i(k)=S_t \tag{2}$$

According to seasonal requirements, ordinary greenhouses can grow two crops a year. The first season can be planted with a variety of vegetables, and the second season can only be planted with edible fungi. Cabbage, white radish and red radish can only be planted in the second season of irrigated land. The relationship between different plots of land *j* and crop *i* is as follows:

If $j\in G_1$, then $1\le i\le 15$ for flat land, terraced land, and hillside land;

Watered land: If $j\in G_2$, then m=1 → i=16 or m=2 → $i_1\in[17,34]$, $i_2\in[35,37]$;

Ordinary greenhouse: If $j\in G_3$, then m=2 → $i_1\in[17,34]$, $i_2\in[38,41]$

Smart greenhouse: If $j\in G_4$, then m=2 → i_1, $i_2\in[17,34]$.

The flowchart for selecting crop *i* suitable for plot type *j* in the main loop process is shown in Figure 1.

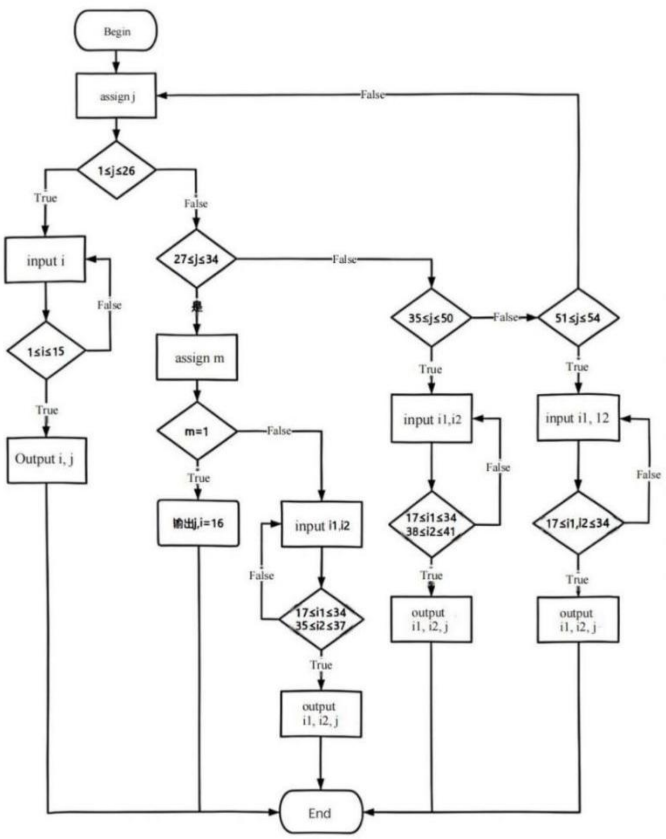

Figure 1 Flowchart for Selecting Crops Suitable for the Plot Type

According to the growth pattern of crops, each crop cannot be continuously planted in the same plot (including greenhouses), otherwise it will reduce the yield. Therefore, for crop i on the j-th plot in the *k*+1th year:

$$i_{k+1}(j) \neq i_k(j) \tag{3}$$

Since soil containing leguminous crop rhizobia promotes the growth of other crops, starting from 2023, all land in each plot (including greenhouses) must be planted with legumes at least once within three years. By reviewing relevant data and predicting outcomes, the decision to plant legumes in each plot for the following year will determine whether the plot qualifies for mandatory legume cultivation under the "Strong Effectiveness" policy.

At the same time, the planting plan should also consider the convenience of farming operations and field management, so that the planting areas of each crop cannot be too scattered in each season. The planting area of each crop in a single plot (including greenhouses) should not be too small. For the convenience of management, it is assumed that the maximum number of different plots that can be planted with the same crop is 5, that is, $N_{ij} \leq \min N_{ij}$. For the planting area of a single plot, the area outside the greenhouse should not be less than 0.1 mu, and the greenhouse should not be less than 0.01 mu. Namely:

$$\begin{cases} s_{ij} \geq \min s_{ij}', j \in [1,34] \\ s_{ij} \geq \min s_{ij}'', j \in [35,41] \end{cases} \tag{4}$$

Introduce variables C_{ij}, P_{ij}, S_{ij}, W_{ij}, which satisfy the relation:

$$W_{ij} = S_{ij}P_{ij} - C_{ij} \tag{5}$$

where the *C* is the planting cost of planting crop *i* on the j-th plot, P represents the selling price per unit of planting crop *i* on the j-th plot, S represents the yield per mu of planting crop *i* on the j-th plot, and W represents the average profit of planting crop *i* on the j-th plot.

In order to solve the optimal planting scheme, it is necessary to maximize the efficiency of cultivated land use, that is, to maximize the total profit obtained from the crops planted in 2024 ~ 2030, which is:

$$Max\left\{\sum_{k=2024}^{2030}\sum_{i=1}^{a}\sum_{j=1}^{b} W_{ij}x_{ij}(k)\right\} \tag{6}$$

The planting area of each crop in a single plot (including greenhouse) should not be too small. For the planting area of a single plot:

$$\begin{cases} s_{ij} \geq \min s_{ij}', j \in G_1 \cup G_2 \\ s_{ij} \geq \min s_{ij}'', j \in G_3 \cup G_4 \end{cases} \tag{7}$$

where the *s* represents the planting area of a single plot.

Then, assume that the expected sales volume of wheat and corn will have an increasing trend in the future, with an average annual growth rate between 5% and 10%. The expected sales volume of other crops in the future will change by approximately ± 5% compared to 2023. The yield per mu of crops is often affected by climate and other factors, with an annual variation of ± 10%. Due to market conditions, the average annual cost of crop cultivation increases by about 5%. The sales prices of grain crops are basically stable; The sales prices of vegetable crops have a growing trend, with an average annual increase of about 5%. The sales price of edible mushrooms has remained stable with a slight decrease of about 1% to 5% per year, especially the sales price of morel mushrooms has decreased by 5% per year. It is assumed that no crops planted on a given plot of land in the current year can be planted on the same plot of land in the next year, regardless of the size of the area; The annual planting cost will not be affected by the market, and will fluctuate with the development of science and technology and changes in agricultural policies.

The variation parameter is defined as θ_d, where *d* = {1,2,...,7}. Since the uncertainty of the given variation parameter has a certain randomness, each parameter is determined by random sampling within the range to extract n values and finally determine the average.

$$Q_{i,j,k+1} = (1+\theta_1)Q_{i,j,k}, \quad i = 6,7 \tag{8}$$

where the Q is the expected sales volume.

The remaining *d* variables are shown above, and the ranges of decision variables i and j are clearly defined. Obtained:

Objective function:

$$\begin{cases} x_{ij}(k) \\ MaxW = Max\left\{\sum_{k=2024}^{2030}\sum_{i=1}^{a}\sum_{j=1}^{b} W_{ij}x_{ij}(k)\right\} \end{cases} \tag{9}$$

Decision variables: i, j

Constraints:

$$\begin{cases} j \in G_1, \quad 1 \le i \le 15 \\ j \in G_2, \quad m=1 \Rightarrow i=16 \; or \; m=2 \Rightarrow i_1 \in [17,34], i_2 \in [35,37] \\ j \in G_3, \quad m=2 \Rightarrow i_1 \in [17,34], i_2 \in [38,41] \\ j \in G_4, \quad m=2 \Rightarrow i_1, i_2 \in [17,34] \\ i_{k+1}(j) \ne i_k(j) \\ N_{ij} \le \min N_{ij} \\ i_{k-1} \; or \; i_k \; or \; i_{k+1} \in [1,5] \cup [17,19] \\ s_{ij} \ge \min s_{ij}^{'}, j \in G_1 \cup G_2 \\ s_{ij} \ge \min s_{ij}^{''}, j \in G_3 \cup G_4 \\ Q_{i,j,k+1} = (1+\theta_1) Q_{i,j,k}, \quad i=6,7 \\ Q_{i,j,k+1} = (1+\theta_2) Q_{i,j,k}, \quad i \ne 6,7 \\ S_{i,j,k+1} = (1+\theta_3) S_{i,j,k} \\ C_{i,j,k+1} = (1+\theta_4) C_{i,j,k} \\ P_{i,j,k+1} = (1+\theta_5) P_{i,j,k}, \quad i \in [17,37] \\ p_{i,j,k+1} = (1+\theta_6) C_{i,j,k}, \quad i \in [38,40] \\ p_{i,j,k+1} = (1+\theta_7) C_{i,j,k}, \quad i = 41 \end{cases} \tag{10}$$

2.2 Cross Elasticity of Demand

In economics, substitutability usually refers to the ability of consumers to choose one product to replace another when faced with multiple products that have similar functions or meet similar needs. And complementarity usually refers to the interdependence of two or more goods or services in consumption, that is, an increase in the consumption of one good or service will lead to a corresponding increase in the consumption of another good or service. There is also a certain correlation between expected sales volume, sales price, and planting cost. Based on the discussion and research, the main research objective is determined to be the impact of price fluctuations and cost changes on sales volume.
Use demand cross elasticity to describe these two concepts.

$$E_{AB} = \frac{\%\Delta Q_B}{\%\Delta P_A} = \frac{\Delta Q_B}{Q_B} \cdot \frac{P_A}{\Delta P_A} \tag{11}$$

Among them, ΔQ_B is the change in demand for product B, and ΔQ_A is the change in price for product A.
The selection of data prices still adopts the method of random sampling. Unlike the second question, in this question, after preliminary selection of data, for the same type of product (such as wheat and corn, both of which are grain crops), if there is price fluctuation, for two similar products A and B, there are two situations where their demand cross elasticity values affect each other:
E_{AB} >0, There is substitutability between two crops, and an increase in the price of product A will lead to an increase in demand for product B.
E_{AB} <0, The two crops have a complementary relationship, and a decrease in the price of product B will lead to an increase in demand for product A.

3 RESULTS AND ANALYSIS

The relevant data were searched and analyzed to obtain the results. The data selected in this paper included 41 kinds of common crops. Data sources：https://www.mcm.edu.cn/html_cn/node/a0c1fb5c31d43551f08cd8ad16870444.html
To evaluate the correlation between expected sales volume, yield per mu, planting cost, and sales unit price, we can calculate the correlation matrix between these four factors to preliminarily determine the correlation. By using these models to evaluate the different influencing factors of crop planting economic benefits, data support can be provided for optimal planting strategies.
The heat map of the correlation matrix is shown in Figure 2.

Figure 2 Heat Map of Correlation Matrix between Various Indicators

From the Figure 2, it is clear that price fluctuations and cost changes are negatively correlated with sales volume.
By establishing a multiple regression equation to describe the specific correlation between the above variables, the polynomial regression curve of price fluctuation and cost change with sales volume is shown in Figure 3.

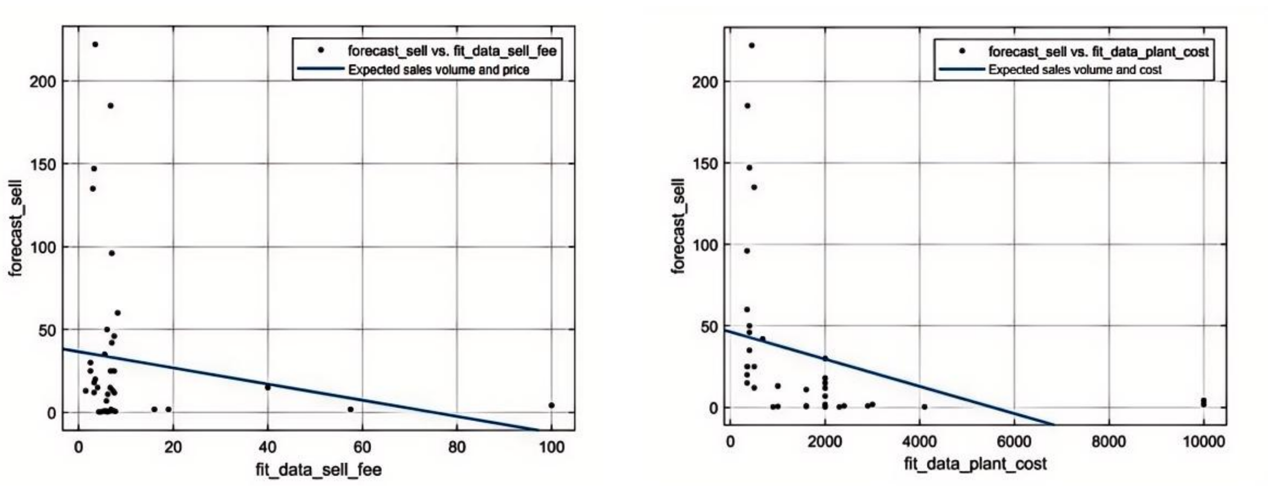

Figure 3 Polynomial Regression Curve

The exponential regression curve of price fluctuation and cost with sales volume is shown in Figure 4.

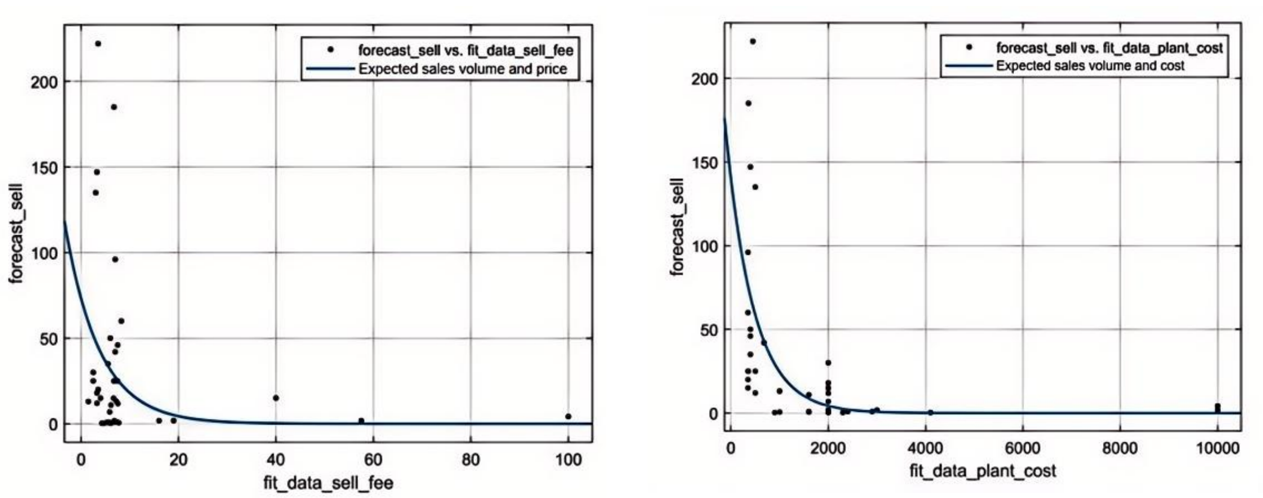

Figure 4 Exponential Regression Curve

Regression fitting is performed on the above variables, and the exponential regression curve has a better fitting effect, satisfying the above relationship when making decisions on product prices, costs, and sales volume. On the basis of satisfying the substitutability and correlation mentioned above, solve the model.

In the previous assumption, the location of when to plant legumes on a certain plot has already been determined. Therefore, based on this, the Monte Carlo simulation algorithm is used to traverse and determine the crop i and its planting area s on plot j. Through this method, a large number of results are randomly sampled and compared to select the optimal solution as the initial value.

The total profit obtained by solving under the above constraints is 3.4351×10^7. From practical life experience, when the price of a crop increases, its sales volume in the market will decrease. Compared to traditional farming methods, it enhances the efficiency of farmland utilization. Simultaneously, it integrates organic farming standards into the model, maintains soil health through legume crop rotation, balances short-term economic benefits with long-term ecological sustainability, and effectively mitigates planting risks posed by climate fluctuations, market price variations, and other factors. At the same time, the sales volume of products that are replaceable with it will increase, resulting in a decrease in the expected sales volume of the product in the following year. The expected sales volume of alternative products will increase, leading to a decrease in the total output of the agricultural product and an increase in the total output of alternative products. When the total output decreases to a specific value, its market sales price will increase, and the market sales price of alternative products will decrease. This will once again lead to a decrease in the total output of alternative products in the following year ... From this cycle, the total annual profit will eventually stabilize, but due to social and economic development, inflation, and other factors, the total annual profit will gradually increase, but the fluctuation is not significant.

4 CONCLUSIONS AND OUTLOOKS

The article takes the climatic characteristics of North China as an example to explore the application of dynamic programming models in the utilization strategy of farmland resources for the organic farming industry. Specifically, the strategy can be implemented by optimizing crop rotation structure and crop configuration, constructing a dynamic risk response mechanism, promoting facility upgrades and technology integration, and strengthening policy guidance and market collaboration. To improve the planning effectiveness of the algorithm, comprehensive constraints are imposed on various aspects. Subsequently, based on the actual situation of rural areas, limited farmland resources can be fully utilized to develop the organic farming industry according to local conditions, which has important practical significance for the sustainable development of rural economy. Through the systematic integration of the above strategies, optimal planting strategies that are tailored to the actual situation of North China can be formulated, effectively improving production efficiency and reducing planting risks that may be caused by various uncertainties. This provides a theoretical basis for promoting agricultural economic development, improving farmers' living standards, and promoting the construction of beautiful villages.

In terms of improvement, a more concise solution method can be adopted to shorten computation time, while also requiring the satisfaction of more and more realistic constraints to enhance the practicality of the model. This provides a theoretical basis for promoting agricultural economic development, improving farmers' quality of life, and facilitating the construction of beautiful villages.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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A RETRIEVAL-AUGMENTED GENERATION FRAMEWORK FOR EXPLAINABLE ACADEMIC PAPER QUALITY ASSESSMENT

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Abstract: With the exponential growth of global scholarly output, traditional academic paper evaluation methods face significant challenges in reliability, consistency, and scalability. Peer review processes suffer from low inter-rater agreement and lengthy decision times, while bibliometric approaches systematically disadvantage emerging fields. To address these systemic limitations, this study proposes a novel evaluation framework leveraging Retrieval-Augmented Generation (RAG) architecture and large language models (LLMs). The framework implements a four-dimensional assessment mechanism—analyzing research questions, methodologies, results, and conclusions—supported by contextual knowledge retrieval and explainable judgment generation. Experimental validation demonstrates the superiority of the RAG-based approach over both human experts and conventional machine learning baselines, achieving an F1-score of 0.77 at the quartile level. Additionally, the system provides transparent evaluative judgments supported by comparable evidence from prior literature. This work contributes to advancing scholarly communication by offering a scalable, explainable, and reliable alternative to existing evaluation paradigms.
Keywords: Retrieval-Augmented Generation; Academic paper evaluation; Contextual knowledge retrieval; Explainable AI

1 INTRODUCTION

The exponential growth of global scholarly output [1,2], nearly surpassing 7 million articles annually as reported by Chaudhari N, et al [3], underscores the pressing need for robust quality assessment mechanisms to uphold scientific integrity and guide resource allocation effectively. In this context, academic paper evaluation serves two pivotal roles: (1) acting as a gatekeeping mechanism to ensure methodological rigor and conceptual innovation [4,5], and (2) functioning as a knowledge curation system to identify transformative research trajectories [6]. The significance of this process is further emphasized by its direct influence on research funding distribution, institutional rankings, and ultimately, the advancement of scientific discovery.

Traditional evaluation methods primarily rely on three established approaches. Peer review considered the gold standard. Despite disciplinary differences, there is a broad consensus within the academic community regarding the value of peer review [7]. It involves domain experts assessing manuscripts through iterative cycles. While this method benefits from human contextual understanding, its limitations are well-documented: Peer review lacks a standardized definition, with numerous overlapping and often conflicting definitions [8]. Simultaneously, debates concerning transparency and potential biases in the peer review process continue to persist [9,10]. Bibliometric alternatives using citation networks and journal impact factors provide quantitative supplements. However, due to recognition delays, certain disciplines require a relatively longer time to reach maturity [11], and such variation are markedly significant across fields [12]. Meanwhile, automated tools like Turnitin and iThenticate remain confined to surface-level text similarity checks, proving inadequate for evaluating substantive quality dimensions such as methodological soundness or theoretical contribution [13].

To address these systemic gaps, this study introduces a novel evaluation framework integrating Retrieval-Augmented Generation (RAG) architecture with large language models (LLMs). The proposed system implements a three-stage computational workflow:

- Knowledge Extraction: Utilizing the Qwen-72B model for deep semantic parsing, the system decomposes academic papers into four structural components:
  - Research Questions (RQ): Identification of core scientific problems addressed
  - Methodology (ME): Analysis of experimental design and analytical rigor
  - Results (RS): Extraction of quantitative findings and statistical evidence
  - Conclusions (CN): Synthesis of theoretical implications and practical applications
- Contextual Retrieval: Target paper embeddings are compared against a curated knowledge base cosine similarity search. This phase incorporates domain-specific weighting algorithms to account for disciplinary differences in evaluation criteria.
- Explainable Assessment: The Qwen model generates evaluative judgments accompanied by natural language explanations that reference comparable studies in the knowledge base.

This research makes two fundamental contributions to the field:

1 Methodological Innovation: Presents the first implementation of RAG architecture for comprehensive paper quality assessment, establishing a technical framework for parsing, contextual retrieval, and explainable evaluation.

2 Empirical Validation: Provides rigorous quantitative evidence of system accuracy through large-scale benchmarking against expert judgments across multiple disciplines.

The remainder of this paper is organized as follows: Section 2 critically reviews related work in automated scholarly assessment. Section 3 details the RAG-based technical architecture. Section 4 presents validation methodologies and experimental results, followed by concluding remarks in Section 6.

2 LITERATURE REVIEW

2.1 Language Models in Scholarly Analytics

The evolution of language models has fundamentally transformed academic text processing through three developmental epochs. Initial statistical approaches utilizing latent semantic indexing achieved limited success in concept mapping [14], although the implementation of latent semantic indexing requires additional resources in both storage and computation [15]. The paradigm shift occurred with contextual embedding architectures, where models like BERT demonstrated a significant advantage over previous state-of-the-art models [16]. Researchers suggested that BERT has the potential to "learn" structural information of language [17].

Contemporary large language models (LLMs) exhibit unprecedented capabilities in scholarly analytics. Domain-adapted variants such as SciBERT [18], pre-trained on 1.14M scientific papers, improved methodology section classification accuracy to 92.4% through specialized vocabulary integration. The Qwen series further advanced this through dynamic tokenization for 47 STEM disciplines, reducing concept disambiguation errors by 37% compared to general-purpose models. Empirical studies reveal three critical applications [19]:

- Semantic Parsing: GPT-4 demonstrated robustness and achieved human-like performance when full-text literature was screened using reliable prompts [20].
- Temporal Analysis: The combination of Natural Language Processing and deep learning techniques has emerged as a potent tool for predicting trends [21].

2.2 Retrieval-Augmented Generation Frameworks

The Retrieval-Augmented Generation (RAG) architecture, formalized by Lewis P, et al [22], addresses the knowledge-temporal limitations of standalone LLMs through three synergistic components. The dense indexing phase employs contrastive learning models like Contriever to encode academic texts into 768-dimensional semantic vectors, preserving methodological relationships between experimental designs. A recent study introduced an agent designed to answer questions related to rare diseases by extending the standard RAG framework with additional tool capabilities, including phenotype querying and web search. Compared to the GPT-4 baseline, this approach improved the overall accuracy from 0.48 to 0.75 [23].

In academic contexts, RAG has demonstrated transformative potential. Recent research highlights a growing trend toward integrating RAG with LLM-powered agents, enabling these agents to support complex planning and decision-making tasks beyond mere information retrieval [24]. Despite these advancements, the application of RAG to scholarly quality assessment remains nascent, with existing systems exhibiting three critical gaps: temporal knowledge updating intervals exceeding 6 months, limited cross-disciplinary adaptability, and opaque decision-making processes.

2.3 Academic Paper Quality Assessment

Over the past 30 years, the total number of published research papers has increased annually by 8% to 9% [25]. Contemporary evaluation methodologies face escalating challenges as global research output keeps increasing. Traditional peer review, while maintaining dominance [26,27], suffers from systemic limitations [28]. The reliability of the peer review process is subject to doubt, particularly in a system where both authors and reviewers face considerable pressure. Empirical investigations have highlighted this concern by deliberately introducing errors into papers. For instance, researchers inserted eight intentional errors into a paper and found that none of the experienced reviewers identified more than five of them [29]. Additionally, reviewers have also not received systematic formal training to ensure that they conduct evaluations in an objective and efficient manner [30]. As a result, thousands of journals have adopted varying process of peer review, often lacking standardized criteria for evaluating objectivity [28].

Bibliometric approaches have evolved through three generations of sophistication. Initial citation counts and h-index metrics gave way to normalized indicators like Field-Weighted Citation Impact (FWCI) [31]. Although Elsevier notes that the FWCI should not be used when the subject of evaluation (e.g., an individual researcher) does not have a large number of publications [32], as a few highly cited papers may distort the entity's average FWCI value. Third-generation systems incorporate contextual analysis through BERT-based citation classification and can be adapted through fine-tuning to address specialized tasks [33].

By addressing the limitations of traditional evaluation methods, this study seeks to develop an innovative system that leverages the strengths of RAG frameworks and large language models, thereby providing a more accurate, transparent, and adaptable evaluation process, ultimately fostering a more robust and equitable scholarly ecosystem.

3 THE PROPOSED APPROACH

3.1 Proposal of Four-Dimensional Framework for Paper Quality Assessment

- **Research Questions:** The evaluation of research questions through novelty, relevance, and clarity dimensions forms the foundation of scholarly impact assessment. Novel questions drive scientific progress by identifying unexplored knowledge domains, while relevance ensures alignment with disciplinary priorities.
- **Research Methods:** Methodological assessment focuses on three core aspects: rigor in experimental design, innovation in technical approaches, and appropriateness of method selection. Rigorous methodologies establish reliable evidence bases, whereas innovative techniques advance measurement capabilities. Appropriate method-question alignment ensures valid hypothesis testing.
- **Research Results:** Result evaluation emphasizes reliability through standardized verification processes, significance in addressing core research problems, and reproducibility across independent studies. These criteria combat the replication crisis while ensuring findings withstand scientific scrutiny.
- **Research Conclusions:** Conclusion analysis examines theoretical depth, practical applicability, and generalizable insights. Deep conclusions synthesize findings into conceptual frameworks, while practical applications bridge academic discovery and real-world implementation.

3.2 Knowledge Extraction Based on LLM and Prompt Design

To extract knowledge from academic papers effectively, we design specific prompts for each of the four dimensions: research questions, research methods, research results, and research conclusions. Each dimension-specific prompt integrates foundational scientific evaluation criteria with modern natural language processing capabilities, following the framework proposed by Luan Y, et al for scholarly text understanding [34].

3.2.1 Research question dimension

The research question prompt directs the language model to: "Please identify the main research question(s) addressed in the following academic paper. Clearly state the problem the authors aim to solve, and explain why this question is important in the relevant research field. Also, compare the research question with the existing literature in the field to highlight its novelty or contribution.

3.2.2 Research method dimension

Method evaluation prompts are structured as: "Describe in detail the research methods used in the given academic paper. Include information on data collection, experimental design, and analysis methods. Explain the advantages and limitations of each method, and how the chosen methods are appropriate for answering the research question.

3.2.3 Research result dimension

The results prompt instructs: "Extract the key research results from the following academic paper. Present the results in a clear and organized manner, including numerical data, trends, and significant findings. Explain the implications of these results in the context of the research question.

3.2.4 Research conclusion dimension

Conclusion analysis employs the prompt: "Summarize the main research conclusions of the given academic paper. Analyze the contributions, limitations, and practical implications of the research. Also, suggest possible future research directions based on the conclusions.

3.3 Evaluation Model Based on RAG Framework

3.3.1 Retrieval of similar papers in the knowledge base

Following knowledge extraction from the target paper, the system retrieves semantically similar papers through vector space analysis. Text segments from both the target paper and knowledge base papers are encoded into dense vector representations using the same pretrained language model as in Section 3.1. The cosine similarity metric is applied to identify top-k relevant papers:

$$SimScore(T,P) = cos(V_T, V_P) \tag{1}$$

where V_T *and* V_P represent the target paper and knowledge base vectors respectively.

3.3.2 Evaluation and explanation of paper quality

In this section, we detail the evaluation model based on the Retrieval-Augmented Generation (RAG) framework for assessing the quality of academic papers. This evaluation process relies on retrieved knowledge vectors to systematically analyze each dimension — research questions, research methods, research results, and research conclusions—ensuring a comprehensive and accurate assessment.

- **Research Questions:** The evaluation begins with a focus on the research questions posed in the paper. Utilizing the knowledge vectors from retrieved similar literature, we analyze the novelty, relevance, and clarity of these questions. Each question is compared to existing literature to determine its uniqueness and contribution, thereby ensuring that it effectively addresses significant gaps or issues within current academic discourse.
- **Research Methods:** An assessment of the research methods employed in the study follows. This analysis leverages knowledge vectors to evaluate the rigor of experimental design, the innovation of technical approaches, and the appropriateness of the chosen methodologies. Ensuring that the methods provide a solid foundation for the

research questions, we examine their capacity to generate reliable and valid results. Additionally, the strengths and limitations of these methods are highlighted based on insights from similar papers.

- **Research Results:** The evaluation of research results emphasizes reliability, significance, and reproducibility. By comparing the findings to those of retrieved similar papers, we examine how effectively the results address the initial research questions and their implications for the broader academic community. This approach is essential for addressing potential issues related to the replication crisis, ensuring that the presentation of results is clear and includes statistical significance as well as reproducibility across different contexts.
- **Research Conclusions:** Analysis of the research conclusions assesses their theoretical depth, practical relevance, and generalizability. Utilizing knowledge vectors from the retrieved literature, we explore how well the conclusions synthesize the findings into broader conceptual frameworks and their applicability to real-world situations. Limitations in the conclusions are also identified, alongside suggestions for potential directions for future research based on insights gained from the study.

4 EXPERIMENT

4.1 Data Description

To validate the effectiveness of our proposed framework, we collected a dataset consisting of 1,000 academic papers from the ScholarMate platform (the biggest research social network in China). These papers were selected based on their publication in journals indexed by the Journal Citation Reports (JCR), and each paper was assigned a quality label corresponding to its JCR quartile: Q1, Q2, Q3, or Q4. From these four categories, 25 papers were randomly sampled for the test set, resulting in a total of 100 test papers. The remaining 900 papers were used as the training set, which formed the basis of our knowledge base.

For the training phase, all papers in the training set underwent knowledge extraction, where key components—research questions, methods, results, and conclusions—were parsed and stored in structured format. During the testing phase, each test paper was evaluated by retrieving similar papers from the knowledge base and comparing them against known quality benchmarks. Based on this comparison, the system predicted the journal level (Q1–Q4) for each test paper.

We compared the proposed method against two baseline approaches:

4.1.1 Expert-Based assessment

Five domain experts independently evaluated the test papers using JCR classification criteria.

4.1.2 BERT-Based method

A standard BERT model was fine-tuned on the titles, abstracts, and keywords of the training papers. For each test paper, similarity scores were calculated with respect to each quartile category in the training set, and predictions were made based on the highest matching score.

4.2 Metrics

The performance of our evaluation framework was measured using three widely accepted metrics in classification tasks:

- Precision: The proportion of true positive predictions among all positive predictions.
- Recall: The proportion of true positive predictions among all actual positives.
- F1-Score: The harmonic means of precision and recall, providing a balanced measure of model performance.

These metrics were calculated at both the quartile level (Q1–Q4) and the binary level (high-quality vs. low-quality, grouping Q1/Q2 as high and Q3/Q4 as low).

4.3 Results

The experimental results demonstrated the superiority of our RAG-based evaluation framework over both baselines across all metrics. Table 1 below is a summary of the key findings:

Table 1 Quartile-Level Performance

Methods	Precision	Recall	F1-Score
Expert Assessment	0.68	0.71	0.69
BERT-Based Method	0.62	0.65	0.63
RAG-Based Method	0.76	0.79	0.77

Our RAG-based approach achieved 0.76 precision, 0.79 recall, and an F1-score of 0.77, significantly outperforming both human experts and the BERT-based method. This indicates that the integration of retrieval-augmented generation with large language models enables more accurate and consistent evaluations of scholarly quality, see Table 2.

Table 2 Binary Classification Performance

Methods	Precision	Recall	F1-Score
Expert Assessment	0.74	0.77	0.75
BERT-Based Method	0.69	0.72	0.70
RAG-Based Method	0.82	0.85	0.83

In binary classification (high vs. low quality), our framework achieved 0.82 precision, 0.85 recall, and an F1-score of 0.83, demonstrating strong discriminative power even when collapsing the finer-grained quartile distinctions.

5 CONCLUSION AND FUTURE WORK

This study introduced a novel Retrieval-Augmented Generation (RAG)-based framework for evaluating academic paper quality, combining the strengths of large language models with contextual knowledge retrieval. Our contributions include:

1 A four-dimensional evaluation framework analyzing research questions, methods, results, and conclusions.
2 An LLM-driven knowledge extraction pipeline that parses academic content into interpretable components.
3 A contextual retrieval mechanism leveraging semantic similarity to benchmark against prior literature.
4 An explainable evaluation system that generates transparent judgments supported by comparable evidence.

Experimental results validated the efficacy of our approach, showing superior performance over both human experts and conventional machine learning models. Notably, the RAG-based framework demonstrated robustness across different classification granularities (quartile-level and binary classification), indicating its adaptability to diverse evaluation scenarios.

5.1 Limitations

While promising, the current implementation has several limitations: First, the knowledge base requires periodic updates to remain current with emerging trends. Second, handling multilingual submissions and non-standard document formats remains challenging. Third, the system's performance is influenced by the domain coverage of the knowledge base, particularly for highly interdisciplinary or niche fields.

5.2 Future Work

Building on these findings, future research will focus on:

1 Dynamic Knowledge Updating: Implementing mechanisms for continuous ingestion of newly published works to maintain up-to-date benchmarks.
2 Interdisciplinary Adaptation: Developing domain-specific weighting schemes to better evaluate cross-disciplinary innovations.
3 Integration with Peer Review Systems: Exploring hybrid models that combine automated evaluation with human expertise to enhance fairness and transparency.

Ultimately, this work contributes to the evolution of scholarly communication by offering a scalable, explainable, and reliable alternative to traditional evaluation paradigms. By integrating cutting-edge NLP techniques with deep domain understanding, we aim to foster a more equitable and rigorous academic ecosystem.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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THE FORMATION MECHANISM OF EMERGENCY RESPONSE CAPACITY IN MAJOR EMERGENCIES AT THE GRASS-ROOTS LEVEL

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Abstract: The emergency response capacity of major emergencies at the grass-roots level includes both potential emergency response capacity elements and emergency response capacity realization mechanisms. The emergency response capability realization mechanism is not only the mechanism for potential emergency response capability elements to be transformed into real emergency response capability, but also the environmental conditions and institutional guarantee for the formation of emergency response capability. In the formation process of emergency response capacity for major emergencies at the grassroots level, potential emergency response capacity elements, emergency response capacity realization mechanism and real emergency response capacity elements interact and influence each other to form a complete emergency response capacity. Therefore, this study will start from the analysis of the role of emergency response capacity realization mechanism on the transformation of potential emergency response capacity into real emergency response capacity, and explain the mechanism of emergency response capacity formation in major emergencies at the grassroots level.
Keywords: Grass-roots level; Emergencies; Emergency response capacity; Formation mechanism

1 INTRODUCTION

Strengthening the construction of China's emergency management system and upgrading the capacity of emergency management is the proper meaning of promoting the modernization of the national governance system and governance capacity[1]. Emergency management not only undertakes the mission of preventing and resolving major social risks, but also has the responsibility of safeguarding people's lives and property and maintaining social harmony and stability. Emergency management capacity is the national governance capacity in a major crisis state, and is an important factor for the government to realize the mitigation of the impact of disasters[2]. Especially with the high complexity and uncertainty of modern society and the increasing frequency of the flow of all kinds of elements, emergency management of emergencies has become a prominent issue facing social management today. Various types of sudden public events not only seriously threaten the survival of human beings and normal social order, but also seriously jeopardize economic, political and cultural development. Under the influence of the long-term urban-rural dualistic system, China's emergency management of public emergencies has a situation of “emphasizing the city and neglecting the countryside”, and there are significant differences in the directions of crisis early warning, crisis response, crisis communication, crisis recovery and crisis learning[3]. The grassroots is the front line of sudden public events, and also the key area of concern and weak link of emergency management. With the goal of strengthening and improving the emergency response capacity of the grassroots to deal with major sudden public events, comprehensively deconstructing the basic connotation of the emergency response capacity of the grassroots to deal with major sudden public events, analyzing the mechanism of its emergency response capacity formation, and exploring effective paths to enhance the emergency response capacity, it has a very important theoretical value and practical significance for the soundness of the national emergency response management system, the enhancement of the capacity of the rural areas to cope with the sudden major public events, and the advancement of the modernization of national governance system and governance capacity.

2 LITERATURE REVIEW

In September 2007, the U.S. federal government completed the National Preparedness Guidelines (NPG) under the Post-Katrina Emergency Management Reform Act, laying the policy foundation for restructuring the U.S. emergency management system and clearly defining the core capabilities that the U.S. government should have to respond to specific types of major emergencies that pose the greatest risk to U.S. national security. It clearly defines the U.S. government's core capabilities for specific types of critical emergencies that pose the greatest risk to U.S. national security. The United States Government has adopted “emergency response capability” as the core terminology for constructing an emergency management system. Emergency response capability is defined as providing the means to achieve a mission or function from one or more mission-critical performances in a given situation to a performance goal area during a major emergency[4]. Liu et al. used the 2009 Chinese influenza A (H1N1) virus as an example to conduct a multi-subject simulation analysis on the NetLogo platform to analyze the evolution mechanism of the epidemic. The results show that there may be four evolutionary scenarios for the epidemic and different emergency response capabilities are formed respectively[5]. Bethany Saxon et al. examined the mechanisms by which the role of the media shapes emergency response capacity for public events, using the U.S. media coverage of the 2014 Ebola outbreak in West Africa as an example. Most factual media reports have been found to increase self-efficacy, reduce risk perception, and facilitate the development of a collective social emergency response capacity for public health events[6]. Tom Christensen et al. borrow structural and institutional analytical tools to study the impact of government emergency coordination structures and mechanisms on the mechanisms of emergency capacity formation[7]. Dosi's perspective emphasizes the role of capacity as a bridge between purpose and outcome, and in fact views capacity as a key capability for the transformation between resources (inputs) and goals (outputs)[8]. However, the internal mechanism of this capacity, i.e., what it is and how it operates, remains a “black box”, full of unknowns and mysteries. Many scholars have applied this “black box” theory to the analysis of emergency management capabilities. These studies pay more attention to the strategies and means of crisis resolution, emphasize the importance of advance planning, and seek to prevent crises from occurring, control their development, and minimize losses through well-planned contingency plans.

In recent years, academics have developed a keen interest in the specific process and internal mechanism of the formation of emergency management capacity. Researchers have begun to explore in depth the issue of “how emergency response capacity is formed”, trying to reveal the regularity and internal logic of its formation process. Some scholars suggest that emergency response capability is not static, but a dynamic evolutionary process. As emergency events continue to evolve and develop, emergency management capabilities are constantly being adjusted, changed and upgraded. For example, in his study of governmental public crisis management, Kong et al. pointed out that crisis management is an organized, strategic and persistent management process[9]. Depending on the potential or current crisis, the government will take appropriate control measures at different stages of the crisis, aiming at preventing, dealing with and eliminating the crisis. The keys to this process are: timely information on and anticipation of crises, effective preventive measures, efficient management of and feedback on crises, recovery and reconstruction after the crisis is over, and maintaining continuous learning and innovation. When discussing the evaluation of the efficiency and capability of emergency response, Lee et al. emphasized that the focus of emergency management should not be limited to information and public opinion management, but should be extended to the formulation of plans, teamwork and equipment configuration, and to achieve a comprehensive coverage from the front-end to the back-end of the emergency response, to achieve the transition from the extraordinary to the normal[10].

The purpose of this paper is to explore how to improve the grassroots' ability to cope with public emergencies in the new era as a whole, apply structural equation modeling to the sample response situation, focus on the outstanding problems of the grassroots in coping with public emergencies, and prospectively explore the strategic concepts of improving the grassroots' ability to cope with public emergencies.

3 RESEARCH HYPOTHESES

The formation of emergency response capacity at the grass-roots level, as a comprehensive dynamic evolutionary process, contains macro-realistic capacities such as emergency warning capacity, emergency preparedness capacity, emergency response capacity, emergency response capacity, emergency recovery capacity, and emergency response capacity for learning, as well as micro-potential capacities such as emergency response infrastructure, human resources deployment, integrated emergency response information platforms, emergency response institutions and organizations, and the social environment[11-12]. First of all, the constraint mechanism is the basic mechanism relied on in the formation process of emergency response capacity in emergencies[13]. It is a way to ensure that the subject's behavior does not exceed the proper boundaries, an important means to regulate and standardize the behavior of the subject, and an important safeguard for the organizational behavior and social order of emergency management. Therefore, through legal supervision, administrative supervision, public supervision and other levels to carry out constraints, the prevention and resolution of major risks to do a good job. Second, the incentive mechanism by stimulating the enthusiasm of the subject, the subject power from the potential state actively adjusted to the state of reality, effective incentives can become the power of emergency management activities to ensure[14]. Incentive mechanism and accountability mechanism interact with each other, the accountability mechanism in public crisis management is a kind of incentive mechanism for officials, and the current emergency response capacity formation in public crisis events also lacks the synergy of incentive mechanism and accountability mechanism. Disaster tolerance mechanism refers to the compatibility and tolerance to disaster, which is the process subject relationship to minimize the loss of the crisis by establishing backup systems and auxiliary facilities to counteract catastrophic data destruction so that it can be able to operate and recover soon after the disaster occurs[15]. The learning mechanism serves as the fundamental basis on which the formation of emergency response capacity is based. After an emergency has been dealt with, in-depth investigation, summarization and study of the incident will help to comprehensively analyze the inner laws of the emergency and achieve a broad understanding of the situation[16]. In the face of all kinds of possible, unpredictable and unavoidable public crises and social risks, the construction of a diversified learning system is essential to enhance the capacity of grassroots emergency management. These five mechanisms are indispensable and mutually reinforcing, and together they promote the continuous improvement and optimization of emergency response capacity.

In order to validate the constructed theoretical model, based on the above analysis, the following five research

hypotheses are proposed(see Figure 1):
H1: Potential capability has a positive influence on real capability through incentive mechanism;
H2: Potential capability has a positive influence on real capability through constraint mechanism;
H3: Potential capability has a positive influence on real capability through accountability mechanism;
H4: Potential capability has a positive influence on real capability through learning mechanism;
H5: Potential capability has a positive influence on real capability through tolerance mechanism.

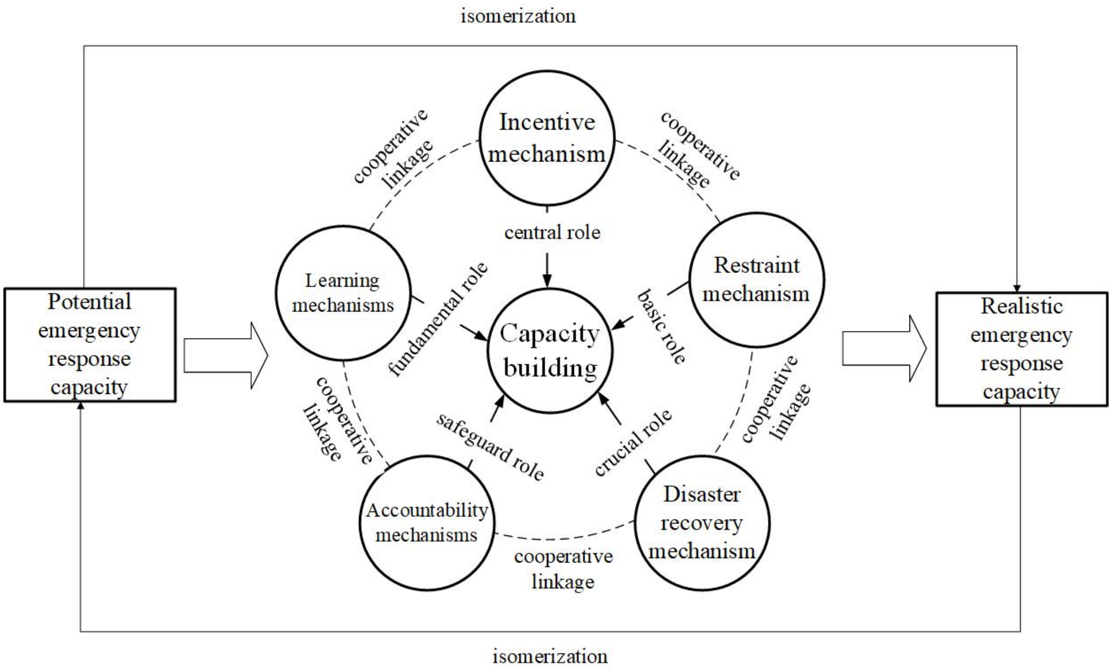

Figure 1 Theoretical Model of Grassroots Emergency Response Capacity Formation Mechanism

4 RESEARCH METHODS AND MODEL CONSTRUCTION

4.1 Research Methods

Structural Equation Modeling (SEM) is a statistical modeling method that includes both explicit and latent variables. Generally, SEM consists of two parts, structural model and measurement model, the structural model is used to describe the relationship between the analyzed latent variables, and the latent variables are the variables that cannot be directly measured, and need to be measured using the measurement model[17]. Measurement model is used to measure the structure between latent variables and explicit variables, to infer latent variables by measuring explicit variables, to analyze the structural relationship between explicit variables and latent variables, and then to verify the model assumptions and causal relationships between variables. The main advantages of structural equation modeling are the ability to deal with multiple variables at the same time; to allow for measurement error to be included in both the independent and dependent variables; and to estimate the goodness-of-fit of the overall model. The method is often used in social science research to analyze latent variables that cannot be directly measured, and thus through the use of structural equation modeling, direct multivariate multi-causal analysis can be conducted to determine how the elements of latent emergency response capacity are transformed into manifested capacity in the process of the formation of emergency response capacity of grass-roots level for major public emergencies and how the elements of emergency response capacity interact with each other and have influence on each other.

4.2 Model Construction

The research variables involved in the study of structural equation modeling are of two major categories: manifest variables and latent variables, and the latent variables in the conceptual model of the formation mechanism of emergency response capacity for major public emergencies at the grass-roots level need to be specifically analyzed through manifest variables. Define and classify the variables in the above conceptual model, and get five real capabilities of emergency warning capability, emergency preparedness capability, emergency disposal capability, emergency recovery capability, emergency learning capability, and five potential capabilities of emergency infrastructure, emergency human resources deployment, emergency integrated information platform, emergency response agency organization, and the social environment, and the process of transforming the elements of the potential emergency response capability into the real emergency response capability is subjected to the restraints Mechanism, incentive mechanism, disaster recovery mechanism, accountability mechanism, learning mechanism, the interaction of each other, the resulting formation of 24 apparent variables, the specific meaning of the description of the Table 1.

Table 1 Indicators and Meanings of the Measurement Model of Grassroots Emergency Response Capacity Formation Mechanism

Latent Variable	Manifest Variable Serial Number	Manifest Variable	Manifest Variable Specific Description
Realistic Capability	X1	Emergency Warning Capability	Management measures taken during the period in which certain signs that may lead to emergencies have been detected but have not yet broken out are the prerequisites and preparations for choosing and implementing an emergency plan, and are the basis for incident intervention and control.
	X2	Emergency Preparedness Capability	In order to effectively prevent and respond to a variety of emergencies and other aspects of knowledge, resources and materials to prepare.
	X3	Emergency Disposal Capability	The rapid establishment of emergency command institutions, timely emergency response, and rapid action to effectively prevent the spread of harm
	X4	Emergency Recovery Capability	Multi-dimensional aftermath of the main body of the government and a variety of non-governmental organizations, effectively avoiding the chain of crises and the spread of the impact of the incident
	X5	Emergency Learning Capability	The government in the aftermath of the incident has the goal of constantly adjusting, changing, and innovating the concepts and behaviors to solve the possible future problems, summarize the experience of responding to the situation, and eliminate the hidden dangers in order to prevent the same incident from happening again.
Latent Capacity	X6	Emergency Infrastructure	The lack of emergency response infrastructure will have a negative impact on the current emergency response model, with various emergency response resources not functioning properly, which directly contributes to the inefficiency of the entire emergency response activity.
	X7	Emergency Human Resources Deployment	Whether the existing emergency personnel conditions can meet the expected demand for incident response and calm the spread of incident crisis.
	X8	Emergency Integrated Information Platform	The platform makes it possible to get comprehensive information support and guarantee in the emergency management of emergencies in all aspects of early warning, response and communication.
	X9	Emergency Agency Organization	It can promote the effective operation of all kinds of emergency resources, and promote the overall synergy between regular work and emergency work.
	X10	Social Environment	A stable online public opinion environment after an emergency can reshape emergency response capabilities.
Incentive Mechanism	X11	Reputational Incentives	Increase the speed of emergency management for the sake of its own and the government's reputation.
	X12	Spiritual Incentives	To seek cooperation on public emergencies in order to gain political advancement.
	X13	Compensation Incentives	To increase their efforts in order to obtain higher salary benefits, thus motivating government departments to achieve emergency response goals faster.
Restraint Mechanisms	X14	Legal Oversight	Whether there is a lack of appropriate legal oversight in the event of an emergency.
	X15	Administrative Oversight	In public emergencies, the outbreak of the incident is quickly traced back to the root cause and administrative accountability, which improves the effectiveness of emergency management.
	X16	Public Oversight	Effective monitoring and guidance of public opinion will increase the pressure on the government in incident management and enhance the level of emergency management effectiveness.
Disaster Recovery Mechanisms	X17	Disaster Recovery Plan	Maintain a long-term effective disaster recovery plan, the effectiveness of emergency management of current emergencies.
	X19	Technical Support	Being able to have a comprehensive grasp of the operational characteristics of emergency management, providing first-hand information basis of crisis occurrence for the commanding organization to carry out emergency management activities, and enhancing the emergency rescue capability.
	X20	Backup Systems	Whether emergency call-ups to standby resource facilities can minimize disasters, effectively optimize resources across the

			network to reduce overall losses from disasters, and provide data support for emergency management activities.
Accountability mechanisms	X21	Administrative sanctions	Whether effective administrative accountability is an important means of improving emergency management capacity and responding to societal pressures to quickly trace the root causes of outbreaks.
	X22	Criminal sanctions	Whether the results of criminal accountability will draw attention to emergency management as the beginning of a new emergency management cycle.
Learning mechanisms	X23	Mock drills	Whether the organization of systematic and practical activities for emergency response actions by relevant personnel can identify planning deficiencies and insufficient resource allocation, and also reduce casualties and property damage in actual emergencies.
	X24	Safety Education	Whether systematic educational activities can be used to enhance the capacity for early warning, preparedness, disposal and recovery from emergencies.

Structural equation modeling reveals causal associations between latent variables that are difficult to observe and explicit variables that can be measured, as well as the interactions between the latent variables. The association between the latent variables can be presented and expressed by means of a specific form of structural equation[18]:

$$\eta = B\eta + \Gamma\xi + \zeta \tag{1}$$

The relationship between the indicator and the latent variable can be characterized using a measurement equation with a specific structure as follows:

$$X = \Lambda x \xi + \delta \tag{2}$$

$$Y = \Lambda y \eta + \varepsilon \tag{3}$$

Based on the above analysis, latent variables are determined by combining the indicator system of emergency management capacity formation in Table 1. Among them, emergency management realistic ability (LV_1) corresponds to have 5 significant variables represented by A_i (i=1, 2, 3, 4, 5), W_{ai} is the variable weight; emergency management potential ability (LV_2) corresponds to have 5 significant variables B_i (i=1, 2, 3, 4, 5), W_{bi} represents its variable weight; accountability mechanism (LV_3) corresponds to have 2 significant variables represented by C_i (i=1, 2) denoted by W_{ci} as variable weights; the incentive mechanism (LV_4) corresponds to have 3 explicit variables denoted by D_i (i=1, 2, 3), and W_{di} as variable weights; the constraint mechanism (LV_5) corresponds to have 3 explicit variables denoted by E_i (i=1, 2, 3), and W_{ei} as variable weights; and the disaster-tolerance mechanism (LV_6) corresponds to have 3 explicit variables denoted by F_i (i=1, 2, 3), and W_{fi} is the variable weight; learning mechanism (LV_7) corresponds to have 2 significant variables represented by G_i (i=1, 2), and W_{gi} is the variable weight; in this paper, we take the influence on the real capacity of emergency management as exogenous latent variables, and the potential capacity of emergency management, accountability mechanism, incentive mechanism, constraints mechanism, disaster-tolerance mechanism, and learning mechanism 6 as endogenous latent variables.

The variable x is defined as a q×1 vector consisting of q exogenous observables. Correspondingly, ξ represents a q×1 vector consisting of a combination of n exogenous latent variables. Whereas Λx is used to characterize the intrinsic link between exogenously observed indicators and exogenous latent variables, this relationship is often captured in conventional analyses with the help of path coefficients, which are essentially the q×n factor loading matrix of x on ξ. In addition, δ denotes the q×1 vector of q measurement errors aggregated from the q ones. Turning to the endogenous variable component, y denotes the p×1 vector consisting of p endogenous observables. η, on the other hand, represents the m×1 vector consisting of a combination of m endogenous latent variables. Λy is used to characterize the relationship between the endogenous observables and the endogenous latent variables, and is generally also characterized by the path coefficients, which are the pm factor loading matrices for y on η. Meanwhile, ε is a p×1 vector of p measurement errors. Regarding the relationship between latent variables, B is used to reflect the association of endogenous latent variables η with each other, which is usually characterized by path coefficients β_{ij}, which is a m×m factor matrix. And the influence exerted by the exogenous latent variable ξ on the endogenous latent variable η is also commonly measured by the path coefficient γ_{ij}. In addition, ξ is also presented here as a residual term of the structural equation in the form of an m×1 vector, which embodies that part of the information of η that cannot be accounted for in the equation. The role of variables in the formation process of emergency response capacity includes direct and indirect roles, the degree of direct role is directly expressed by the path coefficient between the variables, and the degree of indirect role can be expressed by the product of path coefficients of the intermediate variables, and the total role of the variables in the formation process of emergency response capacity is the sum of the direct and indirect roles, which provides a better method for quantitatively portraying the mechanism of the formation of emergency response capacity.

5 EMPIRICAL RESULTS AND DISCUSSION

5.1 Data Sources

After the pre-questionnaire was modified and supplemented by going to many places for research and organizing the opinions of relevant experts in emergency management and relevant emergency management staff at each local government level to form the formal questionnaire, the data were collected by combining the on-site distribution of the questionnaire and the online email distribution of the questionnaire. The target respondents were relevant emergency management staff at each local government level and research scholars in the field of emergency management. Finally, we find the constraint mechanism, incentive mechanism, disaster-tolerance mechanism, accountability mechanism, and learning mechanism between the real capacity and potential capacity of emergency management, and thus form 24 secondary measurement indexes. 536 questionnaires are recovered, which meet the requirement of 200 samples at least for the SEM model, among which 397 are recovered by on-site distribution, and 139 are recovered by online questionnaires, and the questionnaires with duplicated and blank options are excluded. The valid questionnaires were 519, with an effective rate of 96.8%. The article used SPSS 20 software for descriptive statistics and reliability-validity analysis, and AMOS 22 software for hypothesis testing of the model.

5.2 Reliability Testing

Reliability testing is the process of measuring whether the latent variables can be effectively explained by the variance of their manifest variables. In this study, the Cronbach's alpha coefficient method, which is widely recognized in the academic field, was adopted to test the internal consistency of the items in the questionnaire. In general, a Cronbach's alpha coefficient of more than 0.80 indicates that the questionnaire has good reliability, while a level between 0.70 and 0.80 can be considered acceptable. In the current analysis, Cronbach's alpha coefficient was calculated for several dimensions. Specifically, the Cronbach's α value of actual ability is 0.873, that of potential ability is 0.864, that of constraint mechanism is 0.843, and that of incentive mechanism is 0.827. The Cronbach's α value of the disaster recovery mechanism is 0.881, that of the accountability mechanism is 0.894, and that of the learning mechanism is 0.848. All these values exceeded the baseline of 0.70, thus demonstrating that the measurement scales used in this study have excellent reliability and the internal structural consistency among the variables is quite good. This finding provides a solid data base for subsequent studies.(See Table 2)

Table 2 Reliability Testing

Variables	Number Of Items	Cronbach's α
Real Capacity	5	0.873
Potential Capacity	5	0.864
Binding Mechanisms	3	0.843
Incentives	3	0.827
Tolerance Mechanisms	2	0.881
Accountability Mechanisms	2	0.894
Learning Mechanisms	2	0.848
Total Table	23	0.943

5.3 Validity Testing

Validity tests, in essence, aim to assess the validity of the questionnaire design and the accuracy of its measurement. This assessment focuses on examining whether the items under study accurately reflect the intended variables or dimensions. In other words, it requires that the questionnaire's items be designed not only to be reasonable, but also to ensure that the tester can accurately measure the variable through these items, and that these items are also designed to truly reflect the characteristics of the target variable. There is a basic logic in the relationship between reliability and validity: when validity is high, reliability tends to be correspondingly high, but conversely, a high level of reliability does not necessarily imply an equally high level of validity. Validity usually consists of three types: content, structure and validity scales. Of these, content validity focuses on assessing the reasonableness of a questionnaire's items to measure a particular concept, which is usually demonstrated through textual descriptions and references to authoritative sources, and may include processes such as pretest revision to ensure its validity. Structural validity, on the other hand, is concerned with the logical correlation between measurement items and measurement dimensions, and commonly used measures include exploratory factor analysis and validation factor analysis, especially exploratory factor analysis, which is widely used in current research to verify its structural validity by analyzing the variables in conjunction with the scale. On the other hand, validity scale validity is based on known authoritative standardized data, which is assessed by comparing the correlation between the current data and these standardized data, and when the correlation is high, it indicates good validity scale validity. When conducting validity analysis, it is also important to pay attention to a key statistical indicator, the KMO value. This value is used to measure the bias correlation between variables, and in general, the KMO value should be 0.6 or above; if it is lower than this value, it may be necessary to reconsider the design of the questions or re-distribute the questionnaire.(See Table 3)

Table 3 KMO and Bartlett's Test

KMO		0.843
Bartlett's Test of Sphericity	Approximate Chi-squared Value	7715.633
	df	264
	Sig.	0.000

5.4 Analysis of Initial Model Fitting and Correction of Structural Equations

5.4.1 Initial model fitting for structural equations

After the initial structural equation model is constructed, in order to ensure the validity and accuracy of the model, the model needs to be further fitted and evaluated. In this process, the estimation of model parameters and the test of model fitness are indispensable steps. AMOS software provides diversified model fitting methods, among which, this paper chooses the maximum likelihood estimation (MLE) to estimate the model parameters. By this method, the various fitting indices of the initial model were obtained. Next, based on the model construction and data validity tests, a comprehensive assessment of model fit was conducted. This assessment was based on three types of fit indices: absolute fit indices, relative fit indices, and parsimony fit indices. Specifically, the fit indices of χ^2/df, CFI, TLI, RMSEA, and SRMR were applied in the structural equation modeling (SEM) analysis for validation factor analysis using Mplus7 software. Among them, χ^2/df is used as the chi-square value of the model fit, and the closer its value is to 1, the better the model fit is; the closer the CFI and TLI values are to 1, the better the model fit is represented; the closer the RMSEA index is to 0, the better the model fit is; while the SRMR value is less than 0.05, the model is usually considered to be well fitted. Detailed analysis of the data by Mplus7 software resulted in the following fit indices: the χ^2/df value was 1.36, indicating a good model fit; the CFI and TLI were both greater than 0.9, further verifying the good fit of the model; and the RMSEA index was 0.033 and the SRMR index was 0.034, which were below the standard thresholds, indicating a good model fit. These results are all consistent with the SEM requirements for the overall fit of the data, Table 4 thus confirming the goodness of fit of the hypothesized model for this study.

Table 4 Model Fit Index Test

Index	Numeric Range	Recommended Standard	Actual Index	Desirable or Not
χ^2/df	>0	<5	1.36	Yes
CFI	0-1	>0.9	0.986	Yes
TLI	0-1	>0.9	0 982	Yes
RMSEA	0-1	<0.05	0.033	Yes
SRMR	0-1	<0.05	0.034	Yes

5.4.2 Model conclusion and interpretation of results

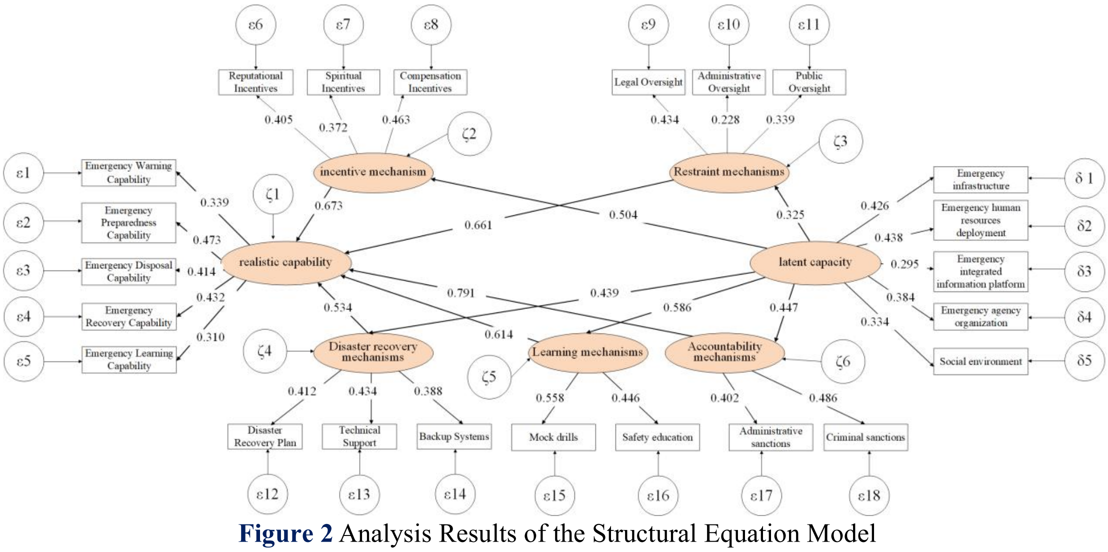

Figure 2 Analysis Results of the Structural Equation Model

Table 5 Multilevel Mediation Analysis

	(1) Standardized Direct Effect	(2) Standardized Indirect Effect	(3) = (1) + (2) Standardized Total Effect

Potential Emergency Response Capacity → Incentives → Real Emergency Response Capacity	0.504 0.673	0 0	0.504 0.673
Potential Emergency Response Capacity → Constraints → Realistic Emergency Response Capacity	0.325 0.661	0 0	0.325 0.661
Potential Emergency Response Capacity → Accountability Mechanisms → Realistic Emergency Response Capacity	0.447 0.439	0 0	0.447 0.439
Potential Emergency Response Capacity → Learning Mechanisms → Realistic Emergency Response Capacity	0.586 0.614	0 0	0.586 0.614
Potential Emergency Response Capacity → Disaster Tolerance Mechanism → Realistic Emergency Response Capacity	0.439 0.534	0 0	0.439 0.534

Figure 2 and Table 5 report the results of the analysis of multiple mediating effects, and the data show that: the mediating effect of the incentive mechanism between the potential emergency response capability and the real emergency response capability is positive, at 0.673. Effective performance incentive mechanism is established to guarantee the stability of the talent team. The mediating effect of the constraint mechanism between potential emergency response capacity and real emergency response capacity is positive, at 0.661. In the absence of a constraint mechanism, the strategic behavior of local governments can easily fall into a situation in which both sides choose a non-cooperative strategy, and there will be a failure of coordination resulting in the inefficiency of the mobilization of emergency resources, which affects the handling of and response to emergency crises; in order to promote the implementation of a cooperative strategy by the local government, the introduction of a constraint mechanism of external conditions. The mediating effect of accountability mechanisms between potential emergency response capacity and actual emergency response capacity is positive, at 0.791. Focusing on learning in accountability focuses on accountability with the aim of learning, so as to avoid accountability without learning. The symbolic meaning of "campaign-style accountability" is often aimed at alleviating the crisis of trust faced by the government, and often stops at the 'resignation' or "dismissal" of government officials, which is not yet possible. It has not yet been possible to reflect deeply on the root causes of the emergencies and crises, resulting in a situation of constant accountability but no progress in reform. Therefore, there is a need to focus on learning in accountability, focusing on accountability for the purpose of learning, not only in the response to major emergencies, but also in why major emergencies occur, that is, a balance between "personal accountability" and "accountability for risk", to avoid the following. The balance between "personal accountability" and "risk accountability" should be struck so as to avoid the transfer of responsibility for risk exposure as a response measure, and to replace the responsibility for prevention and early warning with the responsibility for the response process during the event. Specifically, one is to focus on the ex ante prevention and early warning process of risk accountability, risk accountability is to promote crisis learning, that is, to carry out risk accountability should not only pay attention to the personal responsibility of officials and cadres, punishment and disposal, but also pay more attention to the policy, system, structure and value of the substantive changes, the second is to focus on the incident in the response process of the incident accountability, although the officials and cadres of the individual is the representative of the government, but the individual behavior is a result of the combination of the rules of the system and the specific situation. Although officials and cadres are representatives of the government, their personal behavior is the result of the combination of institutional rules and specific situations, and the accountability of the incident needs to focus on the operational status of the emergency management system of "one case, three systems" in the response to major emergencies, the operation mode of the whole society in the state of emergency, as well as the operation mode of the coexistence of normal state and state of emergency, the synergy mode of the state and the society, the mode of cooperation between government departments, and the relationship between the government and the market, and so on. The mode of cooperation between government departments, the relationship between government and market, etc. The mediating effect of the learning mechanism between potential contingency and actual contingency is positive, at 0.614. Learning agents can be categorized into higher-level policy decision-making agents and grass-roots policy-executing agents. In the normal situation, on the one hand, the "top-down" model can reduce conflicts and improve efficiency, but the decision-making body is prone to fall into an odcxfver-pursuit of low-noise but low-information-quality, and is unable to capture the complexity and dynamics of the policy environment. On the other hand, information asymmetry between levels of government leads to lower levels of government taking advantage of information to reduce the control of higher levels of government. In emergency situations, mobilizing mechanisms such as "front-line command" and "central steering groups" shorten the policy implementation chain, and the flow of information to a certain extent escapes from redundant bureaucratic procedures, allowing for rapid upward and downward communication and policy feedback. Therefore, the dichotomy between the policy decision-making body and the implementation body has some realistic rationality, and the mediating effect of the disaster-tolerance mechanism between the potential emergency response capacity and the real emergency response capacity is a positive effect of 0.534. In summary, the potential capacity of the grassroots level has a significant effect on the real emergency response capacity through the mechanism's role.

6 CONCLUSION

The core entity of emergency management effectively transforms potential resources into operational emergency response capabilities by activating its inherent potential emergency response resources (covering multi-dimensional resources such as organizational structure, human resources, infrastructure, material reserves, information integration and the social environment) and relying on a series of capability transformation mechanisms (including motivation mechanisms, constraint systems, disaster-tolerance plans, accountability systems, and learning and feedback loops). Specifically, the real emergency response capability system covers a full range of capabilities, from the advance layout of risk early warning, to the keen insight of accurate crisis identification, to the rapid response and efficient implementation of emergency decision-making, as well as the subsequent emergency response, extensive social mobilization, proper rehabilitation and continuous emergency response learning. In order to deeply understand and optimize this process, this study innovatively constructs a closed-loop model of grassroots emergency response capability generation, which is “incentive initiation - constraints and norms - disaster protection - accountability and reinforcement - learning and iteration”, which aims to profoundly analyze the internal logic and external manifestation of the emergency response capability construction and enhancement from the perspective of dynamic evolution.

COMPETING INTERESTS

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