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Energy-Saving Research on Battery-Powered Load-Haul-Dump Machine Based on Dual Motor Drive and Intelligent Gear-Shifting Control

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***Abstract*—With the increasing environmental requirements in the mining industry, battery-powered underground Load-Haul-Dump (LHD) machines have become mainstream mining equipment due to their zero emissions and low noise. However, the limited battery capacity poses a critical challenge in improving energy utilization efficiency and extending the working time per charge. This study proposes an energy-saving strategy based on dual motor drive and intelligent gear-shifting control to optimize energy efficiency. Firstly, a model of the LHD's drive system and energy consumption is established to analyze energy usage characteristics under different working conditions. Then, an adaptive genetic algorithm is employed to optimize transmission system parameters. Furthermore, an intelligent energy-saving gear-shifting strategy based on a Backpropagation Neural Network (BPNN) is proposed to achieve precise gear control and reduce energy consumption. Simulation results indicate that the proposed strategy reduces energy consumption per working cycle by 12.7%, significantly enhancing the economic efficiency and operational performance of the LHD. This research provides a theoretical basis and engineering reference for energy-saving control of underground LHDs.**

***Keywords*—battery-powered Load-Haul-Dump (LHD), Transmission system, Energy-saving optimization, Backpropagation Neural Network (BPNN), Intelligent gear-shifting control**

I. INTRODUCTION

With the increasing environmental requirements in the mining industry, battery-powered underground Load-Haul-Dump (LHD) machines have become the mainstream equipment for mining operations due to their advantages of zero emissions and low noise. However, the limited battery capacity poses a significant challenge in improving energy utilization efficiency and extending the operating time per charge, making it a key research focus in this field [1]. Existing studies mainly focus on optimizing the power system and energy-saving control strategies. However, there are still issues such as poor transmission system matching and unreasonable gear-shifting strategies, leading to excessive energy losses [2]. In recent years, various strategies have been proposed for optimizing the energy efficiency of underground mining equipment, particularly electric LHD vehicles. For example, Nieto *et al.* [3] conducted a comparative analysis of the performance between electric and diesel LHDs, finding that electric equipment performs better in terms of maintenance cycles and operating time. Moreover, Mariager *et al.* [4] used Discrete Event Simulation (DES) to study the battery replacement process for electric LHDs in underground mining, emphasizing the impact of operational strategies on system efficiency. In the field of intelligent control, Cai *et al.* proposed a path-following control strategy based on Backpropagation Neural Networks (BPNN), enhancing the control accuracy of vehicles in complex environments [5]. However, existing studies tend to focus on isolated aspects, such as performance comparisons of equipment or optimization of specific control strategies, lacking comprehensive research on the overall energy efficiency optimization of electric LHD systems.

This study aims to fill this gap by proposing an integrated energy-saving control framework that combines dual-motor drive optimization, adaptive transmission ratio adjustment, and BPNN-based intelligent gear-shifting control to enhance the energy efficiency of electric LHDs in practical mining operations.

II. BATTERY-POWERED LHD DRIVE SYSTEM AND ENERGY CONSUMPTION MODEL

The transmission system of an underground Load-Haul-Dump (LHD) machine is a critical factor affecting overall energy utilization efficiency and operational performance. Due to the complex underground mining environment, LHDs must operate under various working conditions, each requiring different levels of power output from the transmission system. This section analyzes the characteristics of several typical working conditions and their respective power demands, establishing a complete

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transportation cycle model for a 3 m³ underground LHD. A dual-motor drive system with a retained hydraulic torque converter is proposed, and a traction motor is selected to establish a gear-energy consumption relationship model.

A. Typical Working Conditions

To improve the working efficiency of underground LHDs, operators typically follow the principles of minimizing travel distance and reducing turning frequency, selecting optimal routes based on the size and location of the ore piles. Therefore, the operation mode of LHDs in underground mining exhibits a certain periodicity. Current LHD operation modes include "L", "T", "I", and "V" patterns [6, 7]. This study takes the "L"-shaped operation mode (illustrated in Fig. 1) as an example to analyze the typical working conditions of underground LHDs.

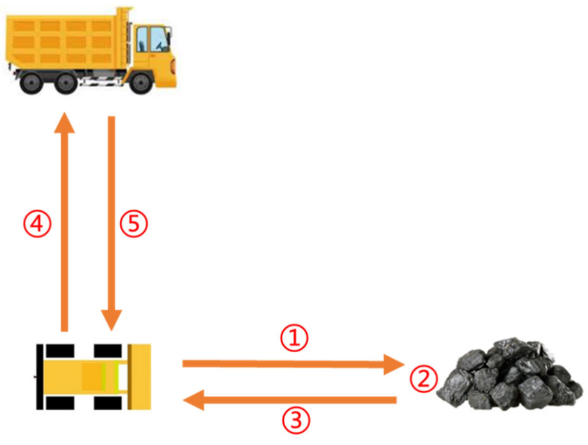


Fig. 1. "L"-shaped operation mode.

The working distance of a single cycle is 150 m. The relationship between the desired vehicle speed, working resistance, and travel displacement of the LHD under cyclic working conditions is illustrated in Fig. 2. The specific working conditions and corresponding component states at each stage are described as follows [8, 9]:

1) Traveling to the ore pile (unloaded movement): The LHD moves from the loading point to the ore pile, where energy consumption is mainly affected by travel resistance.
2) Inserting into the ore pile (loading condition): The motor provides maximum torque at a low speed to push the bucket into the ore pile, resulting in high power demand.
3) Reversing with a full load: After the bucket is fully loaded, the LHD reverses with a high system load.
4) Traveling to the unloading point (loaded movement): The LHD operates at full load, where the transmission system needs to overcome significant resistance, leading to substantial energy consumption.
5) Returning unloaded: After unloading the ore, the LHD returns to the starting point with relatively low energy consumption.

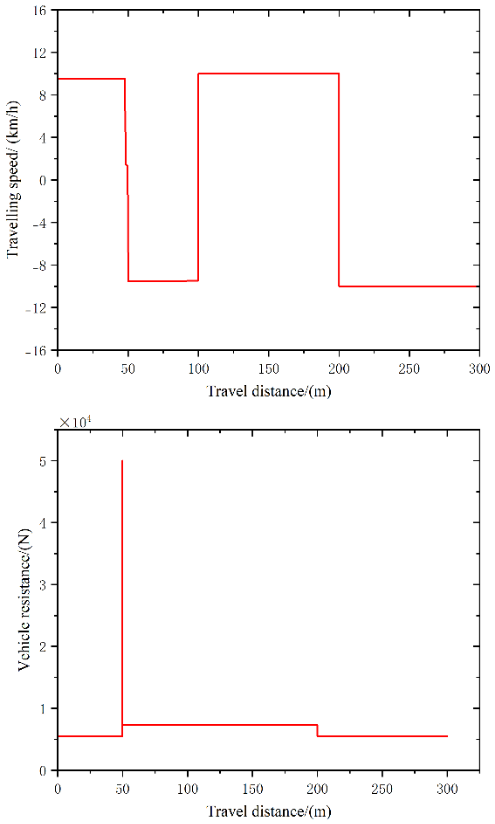


Fig. 2. Scraper cycle working conditions.

B. LHD Transmission System Drive Scheme and Energy Consumption Analysis

The transmission system of a battery-powered underground LHD consists of key components such as a battery pack, motor, hydraulic torque converter, gearbox, and drive axle [10, 11]. Currently, there are two common drive schemes for battery-powered LHDs:

1. Single-motor drive system: In this configuration, a single battery pack and motor power the entire transmission system. After passing through the hydraulic torque converter, the power is split—one part is used to drive the LHD's movement, while the other powers the hydraulic system. In this design, the distribution of energy after motor output must be carefully considered, as an unreasonable allocation can negatively impact the overall energy utilization efficiency.
2. Dual-motor drive system: This configuration uses two motors, with the pump motor powered by an auxiliary battery pack, independently driving the travel and hydraulic systems [12]. This scheme replaces the hydraulic-mechanical transmission with pure mechanical transmission, eliminating the low-efficiency hydraulic torque converter, significantly improving the efficiency of the drive system.

This study integrates the advantages of both transmission systems and proposes a new transmission system (illustrated in Fig. 3) with a focus on energy efficiency. The proposed system operates by utilizing battery power to drive both the travel and hydraulic systems, transmitting power to the wheels through a mechanical transmission mechanism, thereby achieving LHD movement. The system is developed based on the original vehicle structure, offering the advantage of a short development cycle.

The retention of the hydraulic torque converter plays a crucial role in protecting the traction motor from sudden external force impacts encountered in underground operations. This ensures that the traction motor can function properly even under extreme working conditions, improving the overall stability and safety of the drive system.

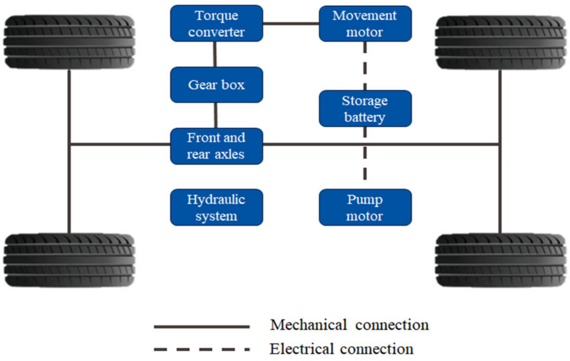


Fig. 3. Schematic diagram of the dual motor structure of the battery-operated downhole scraper.

C. *Traction Motor Parameter Matching*

The motor serves as the power source of an underground Load-Haul-Dump (LHD) machine, directly impacting the vehicle's energy efficiency and dynamic performance [13]. The selection of the motor should be based on the operating environment and power demand of the LHD. If the motor power is too high or too low, it may negatively affect the vehicle's overall performance—either reducing operational stability or causing energy wastage. This study focuses on energy-saving from the transmission system perspective, therefore, the parameter matching analysis is conducted specifically for the traction motor.

During the matching process, the original parameters of a 3m³ cable-drawn underground LHD serve as the baseline, as listed in Table I.

TABLE I ORIGINAL VEHICLE PARAMETERS

Parameter Name	**Value**
Curb weight (kg)	19000
Rated load (kg)	6000
Rated bucket capacity (m³)	3
Wheel radius (m)	0.65
First gear transmission ratio	5.01
Second gear transmission ratio	2.41
Third gear transmission ratio	0.89
Drive axle transmission ratio	26.1

Since the battery pack powers the underground LHD, reducing battery energy consumption requires the traction motor to have high energy conversion efficiency. Additionally, given that the studied vehicle is a retrofitted model with limited space in the rear chassis, the selected motor must be compact and lightweight.

Permanent Magnet Synchronous Motors (PMSMs) exhibit significant advantages in energy conversion efficiency, rotational performance, and power density [14–17]. Therefore, a PMSM is selected as the traction motor for the battery-powered underground LHD.

According to the previous analysis of working conditions, most of the LHD's operating time is spent on flat road transportation. Hence, the rated power of the traction motor is determined based on the maximum speed of the LHD during full-load transport. The required power is expressed as follows:

$$P_e = \frac{\left(G + G'_{\max}\right) f + F_w}{3600\eta_t} v_{\max} (1-\delta)$$

where:

$G'_{\max}$ is the maximum loaded gravity of the loader, N;

$V_{\max}$ is the maximum vehicle speed, km/h.

By substituting the relevant parameters into the equation, the calculated required power is approximately 45 kW. Considering the harsh working conditions and safety factors of the LHD, a PMSM with a rated power of 45 kW is selected. The detailed parameters of the traction motor are listed in Table II.

TABLE II. TRACTION MOTOR PARAMETERS

Parameter Name	Value
Rated power (kW)	45
Peak power (kW)	85
Rated torque (N·m)	140
Peak torque (N·m)	280
Rated speed (r/min)	2800
Peak speed (r/min)	6000

This motor selection ensures that the LHD achieves efficient energy utilization while maintaining sufficient dynamic performance to handle complex underground conditions.

D. *Gear Position and Energy Consumption Model*

Battery-powered Load-Haul-Dump (LHD) machines rely on a single battery pack as their sole energy source. To maximize economic benefits, it is crucial to conserve electrical energy and extend the operational time per charge. Therefore, an in-depth analysis of the relationship between gear position and energy consumption is necessary to establish a corresponding model [18].

Underground LHDs mainly operate in horizontal tunnels, where the gradient is relatively small (3‰–5‰). Since the slope resistance is negligible in most cases, flat-road transportation represents the majority of the LHD's operational cycle. To simplify the gear-energy consumption relationship model, the air resistance is also ignored. Under these conditions, the total traction force required for vehicle movement is primarily used to overcome rolling resistance, leading to the following energy consumption equation:

$$E(X)=\int\frac{(G+G')f}{3600\eta_w\eta_m}\cdot\frac{0.377n_Tr_d}{i_wi_gi_0}(1-\delta)dt$$

where:

r_d is the wheel radius (m);

n_T is the turbine speed of the torque converter (r/min);

i_w is the torque converter speed ratio;

i_g is the gearbox transmission ratio;

i_0 is the final drive ratio (drive axle transmission ratio).

III. TRANSMISSION SYSTEM PARAMETER OPTIMIZATION

To address the energy consumption challenges of Load-Haul-Dump (LHD) machines, this study employs an Adaptive Genetic Algorithm (AGA) to optimize the transmission ratio. The primary goal is to minimize energy consumption per work cycle, with the transmission ratio serving as the key optimization variable.

A. Optimization Objective of the Transmission System

The optimization of the vehicle power transmission system involves solving a mixed-variable nonlinear optimization problem, which is complex and prone to local optimal solutions when using conventional algorithms. The advantages of the Genetic Algorithm (GA) make it an effective approach for solving such problems [19]. Therefore, this study utilizes an Adaptive Genetic Algorithm (AGA) to optimize the gearbox transmission ratio, with the goal of minimizing energy consumption per work cycle. The optimization variables include the gearbox transmission ratios and final drive ratio of the LHD, which are expressed as:

$$x=[i_0,i_{g1},i_{g2},i_{g3}]^T$$

where:

x represents the optimization variables;

i_0 is the final drive ratio;

i_{g1} is the first gear transmission ratio;

i_{g2} is the second gear transmission ratio;

i_{g3} is the third gear transmission ratio.

B. Objective Function and Constraints

The optimization objective is to minimize the energy consumption per work cycle, which serves as the evaluation metric for energy efficiency. The objective function is expressed as:

$$\min E(X)=\sum_{i=0}^{T}\frac{F_i(t)\cdot 0.377n_Tr_d}{3600\cdot i_wi_gi_0\cdot\eta_m\eta_w}$$

where:

x represents the optimization variables. $x=[i_0,i_{g1},i_{g2},i_{g3}]^T$.

To ensure the feasibility of the optimization results, several constraints must be considered when optimizing the transmission system parameters of the LHD. The performance constraints primarily consider maximum vehicle speed and peak power requirements under extreme operating conditions.

(1) Maximum Gradeability Constraint. To meet the maximum gradeability requirement, the first gear transmission ratio must satisfy [20]:

$$i_{g1}\geq\frac{mg(f\cos\alpha+\sin\alpha)r_d}{T_{\max}\eta_ti_0}$$

where:

α is the slope angle (°);

$T_{\max}$ is the maximum output torque of the motor (N • m).

(2) Traction Force Constraint. To prevent excessive traction force that exceeds road adhesion, the first gear transmission ratio must satisfy:

$$i_{g1}\leq\frac{F_k\varphi r_d}{T_{\max}\eta_ti_0}$$

(3) Maximum Speed Constraint: To ensure that the LHD can achieve its maximum operating speed, the third gear transmission ratio must satisfy:

$$i_{g3}\leq 0.377\frac{\eta_{\max}r_d}{V_{\max}\eta_ti_0}$$

where:

$\eta_{\max}$ is the maximum motor speed (r/min);

(4) Gear Ratio Continuity Constraint. To ensure a smooth transition between gears, adjacent gear ratios must satisfy [21]:

$$\frac{i_{gn}}{i_{g(n+1)}}\leq\frac{n_e}{n_{\max}}$$

where:

n_e is the rated motor speed (r/min).

Based on the above constraints, the optimization model is established as follows:

$$\begin{cases}Find\ x=[i_0,i_{g1},i_{g2},i_{g3}]\\ \min E(X)=\sum\limits_{i=0}^{T}\dfrac{F_i(t)\cdot 0.377n_Tr_d}{3600\cdot i_wi_gi_0\cdot\eta_m\eta_w}\\ s.t.\ i_{g1}\geq\dfrac{mg(f\cos\alpha+\sin\alpha)r_d}{T_{\max}\eta_ti_0}\\ i_{g1}\leq\dfrac{F_k\varphi r_d}{T_{\max}\eta_ti_0}\\ i_{g3}\leq 0.377\dfrac{\eta_{\max}r_d}{V_{\max}\eta_ti_0}\\ \dfrac{i_{gn}}{i_{g(n+1)}}\leq\dfrac{n_e}{n_{\max}}\end{cases}$$

C. Optimization Model Solution

Using the genetic algorithm toolbox in MATLAB, the objective function and boundary constraints defined in the previous section are solved. The optimization parameters are set as follows:

- Maximum number of evolution iterations: 50
- Population size: 100
- Binary encoding length: 40 bits
- Selection operator: proportional selection
- Crossover probability: 0.6
- Mutation probability: 0.01

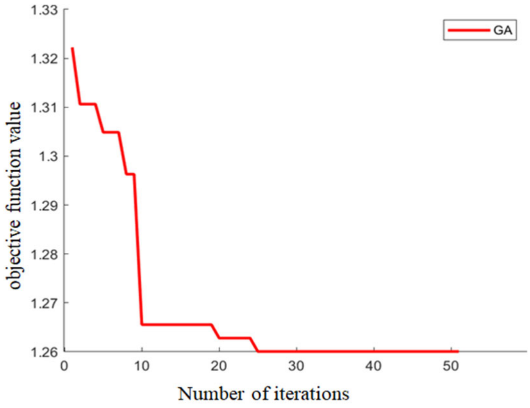


Fig. 4. Optimisation results.

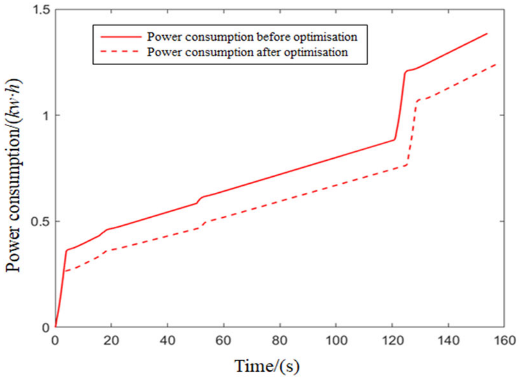


Fig. 5 Comparison of energy consumption before and after optimization.

The final optimization results are shown in Fig. 4, which indicates that the optimal solution for the objective function is achieved after 25 iterations. The comparison of power consumption before and after optimization is illustrated in Fig. 5. It is evident that the optimized energy consumption is lower than before, and the difference in energy consumption increases over time.

After optimization, the energy consumption per work cycle is reduced from 1.39 kWh to 1.26 kWh, representing a 9.4% reduction in power consumption.

IV. INTELLIGENT ENERGY-SAVING GEAR-SHIFTING STRATEGY

The automatic gear-shifting strategy determines the shifting timing of the transmission system, directly affecting the dynamic performance and energy efficiency of the Load-Haul-Dump (LHD) machine. Due to the complex underground mining environment, manual gear shifting requires operators to constantly assess speed, acceleration, and road conditions, which increases their workload and reduces operational efficiency. An automatic transmission system can autonomously complete information collection, gear selection, and shifting execution, thereby reducing operator workload and enhancing vehicle performance [22, 23].

This study proposes an energy-saving gear-shifting strategy based on the actual operating conditions of battery-powered underground LHDs. The strategy ensures that the hydraulic torque converter always operates in a high-efficiency range and utilizes a Backpropagation Neural Network (BPNN) to optimize the automatic transmission system, achieving precise energy-saving gear shifting and improving operational efficiency and energy utilization.

A. Backpropagation Neural Network Model

Studies have shown that gear selection affects the efficiency of the hydraulic torque converter, which in turn impacts overall vehicle energy consumption [24]. This study proposes an energy-saving gear-shifting strategy based on the operating conditions of underground LHDs. By intelligently controlling gear shifting, the motor and hydraulic torque converter are maintained within their high-efficiency operating ranges, reducing overall energy consumption.

To optimize the gear-shifting strategy, the motor speed (n_e), vehicle speed (v), and accelerator pedal position (α) are selected as the input parameters of the intelligent gear-shifting control system. Since the LHD transmission system consists of three gears, a three-input, three-output BPNN model is developed, as illustrated in Fig. 6.

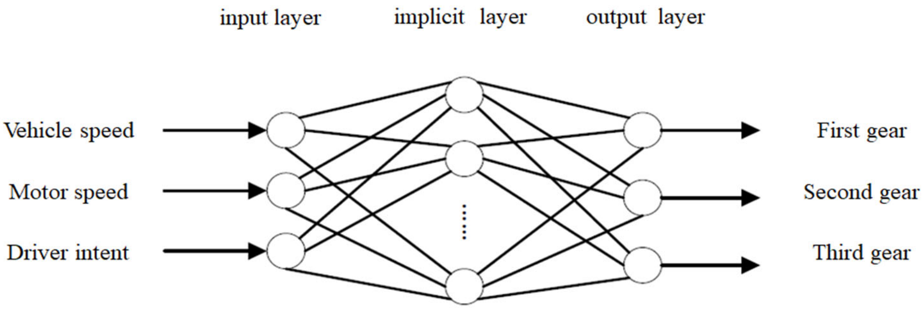


Fig. 6. Energy-saving gear-shifting control based on backpropagation neural network model.

B. Simulation Model Development

Based on the mathematical model of the LHD transmission system and the dynamic equations governing vehicle motion, a simulation model is developed in Simulink. The simulation framework includes: Traction motor model, Hydraulic torque converter model, Power-shift transmission model, Vehicle dynamics model, Driver model, Gear-shifting control model. These components are integrated into a complete simulation model of the automatic transmission system for battery-powered LHDs, as shown in Fig. 7.

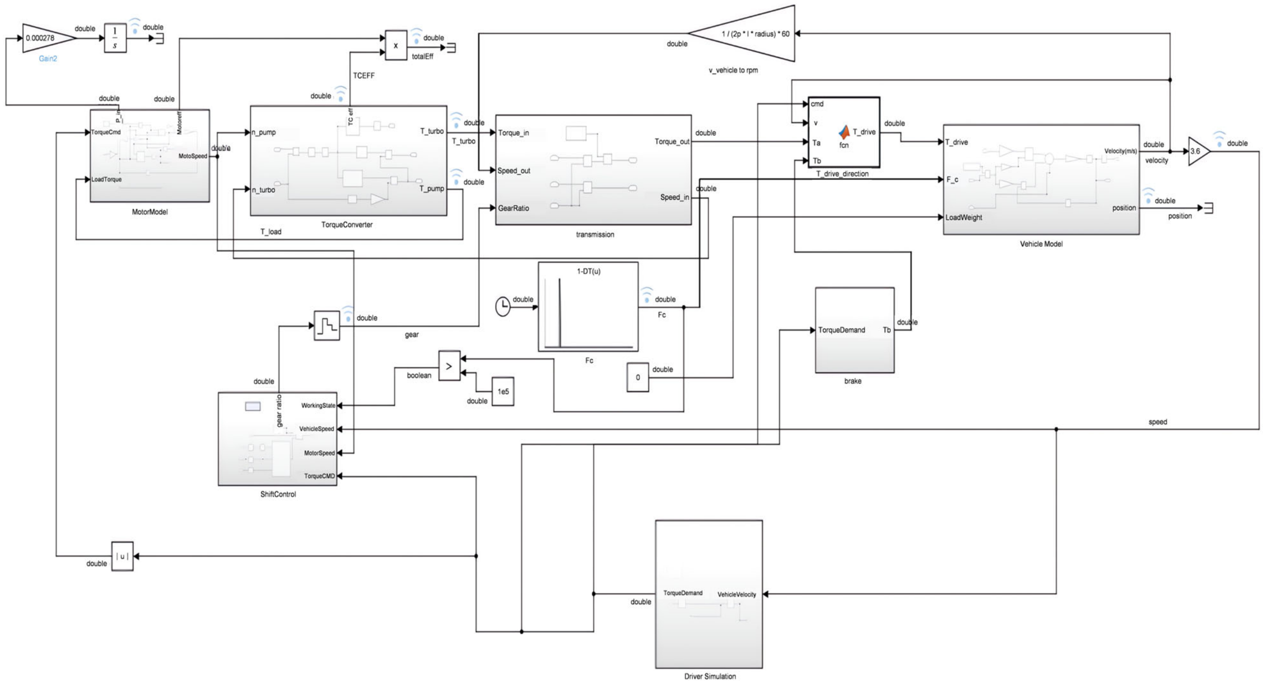


Fig. 7. Simulation model of the automatic transmission system for battery-powered underground LHD.

The simulation environment was developed in MATLAB/Simulink and includes integrated submodules for traction motor control, hydraulic torque converter, transmission, vehicle longitudinal dynamics, and gear-shifting logic. The simulation cycle replicates a typical 150-meter "L"-type operation route used in underground mines, covering loading, transporting, and unloading phases. Parameter selection for the traction motor, gearbox, and drive axle was based on actual data from a 3 m³ cable-drawn LHD model. The rated motor power of 45 kW was calculated based on vehicle mass, load capacity, and full-load top speed, ensuring it meets the maximum power demand. Gear ratios and vehicle resistance parameters (e.g., rolling resistance coefficient, wheel radius) were taken from standard manufacturer catalogs and validated through engineering design references. The genetic algorithm optimization was executed over 50 iterations, using population sizes and mutation probabilities aligned with common practice in vehicular powertrain optimization studies. These simulation settings and parameter foundations ensure that the model is both representative and reproducible, laying a solid groundwork for future experimental validation and industrial application.

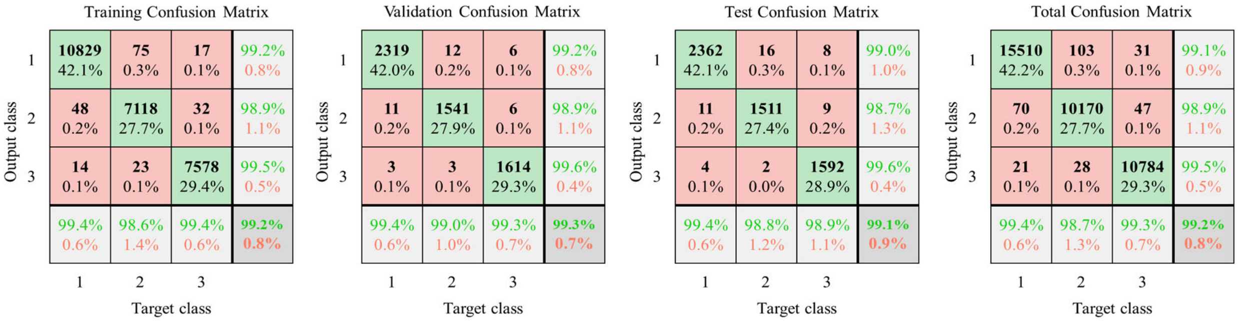
C. Simulation Analysis

1) Training data source

Using the energy-saving gear-shifting strategy proposed in this study, a data set of optimal energy-saving shifting points is generated. This data includes: Motor torque demand, Motor speed, Vehicle speed, Accelerator pedal position, Optimal real-time gear position. The dataset is then imported into MATLAB's neural network toolbox for training

2) Neural network training

In the training process, the input consists of three features (motor speed, vehicle speed, and accelerator pedal position) with 36,764 observations in a double-precision array. The output consists of three gear categories, also with 36,764 observations in a double-precision array. The data is randomly divided into training, validation, and testing sets, with the training algorithm using scaled conjugate gradient descent, and the cross-entropy error as the performance evaluation metric. The training process is configured with five hidden layers, and the final results are shown in Fig. 8.



Training Confusion Matrix

	1	2	3	
1	**10829** 42.1%	**75** 0.3%	**17** 0.1%	99.2% 0.8%
2	**48** 0.2%	**7118** 27.7%	**32** 0.1%	98.9% 1.1%
3	**14** 0.1%	**23** 0.1%	**7578** 29.4%	99.5% 0.5%
	99.4% 0.6%	98.6% 1.4%	99.4% 0.6%	**99.2%** **0.8%**

Output class

Target class

Validation Confusion Matrix

	1	2	3	
1	**2319** 42.0%	**12** 0.2%	**6** 0.1%	99.2% 0.8%
2	**11** 0.2%	**1541** 27.9%	**6** 0.1%	98.9% 1.1%
3	**3** 0.1%	**3** 0.1%	**1614** 29.3%	99.6% 0.4%
	99.4% 0.6%	99.0% 1.0%	99.3% 0.7%	**99.3%** **0.7%**

Output class

Target class

Test Confusion Matrix

	1	2	3	
1	**2362** 42.1%	**16** 0.3%	**8** 0.1%	99.0% 1.0%
2	**11** 0.2%	**1511** 27.4%	**9** 0.2%	98.7% 1.3%
3	**4** 0.1%	**2** 0.0%	**1592** 28.9%	99.6% 0.4%
	99.4% 0.6%	98.8% 1.2%	98.9% 1.1%	**99.1%** **0.9%**

Output class

Target class

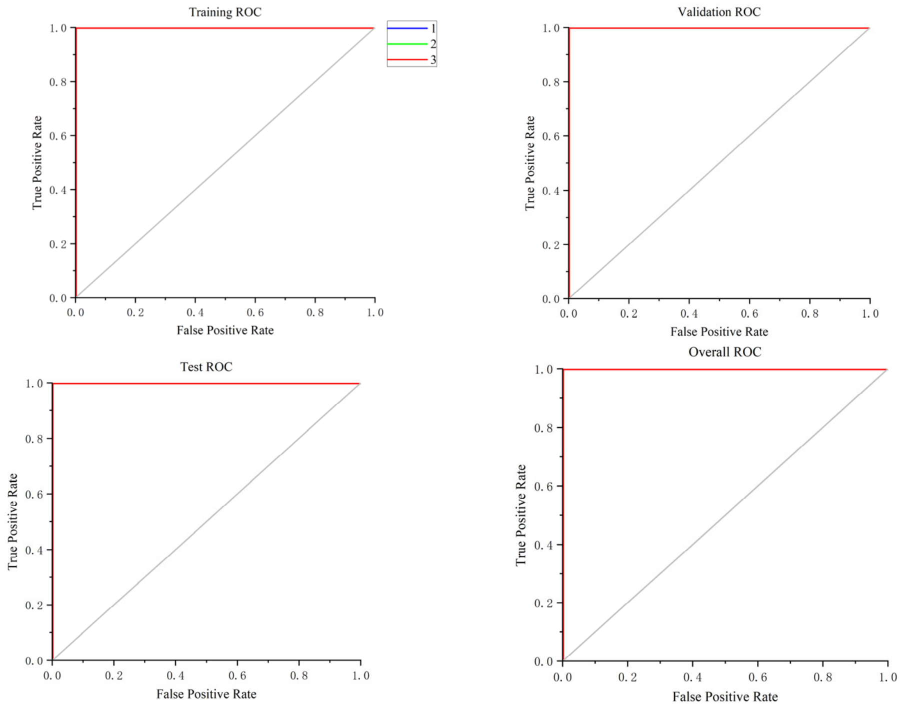
Total Confusion Matrix

	1	2	3	
1	**15510** 42.2%	**103** 0.3%	**31** 0.1%	99.1% 0.9%
2	**70** 0.2%	**10170** 27.7%	**47** 0.1%	98.9% 1.1%
3	**21** 0.1%	**28** 0.1%	**10784** 29.3%	99.5% 0.5%
	99.4% 0.6%	98.7% 1.3%	99.3% 0.7%	**99.2%** **0.8%**

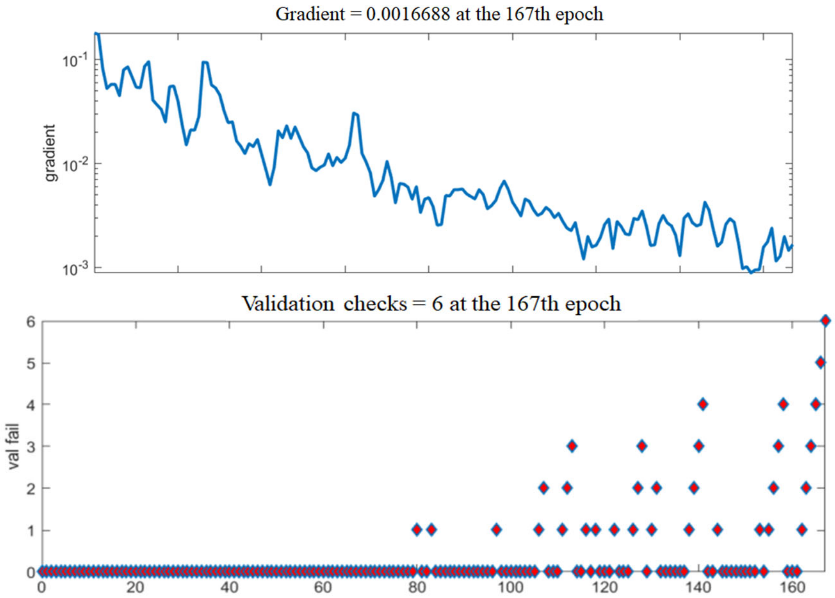
Output class

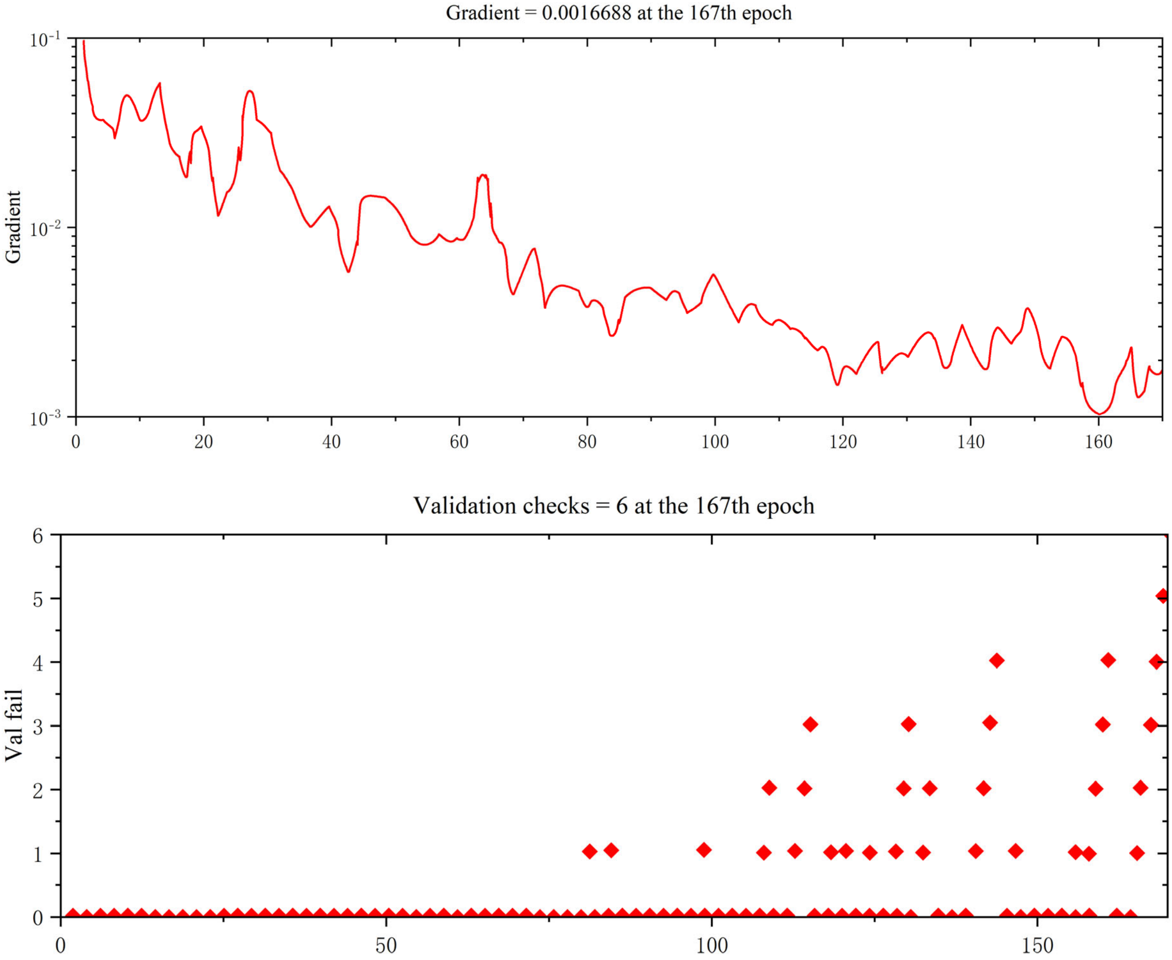
Target class

(a)

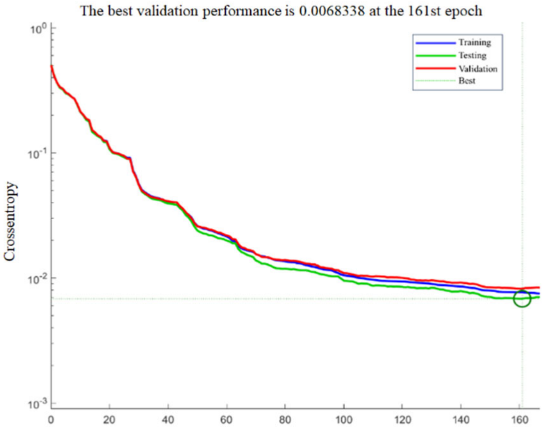


(b)




Gradient = 0.0016688 at the 167th epoch
Gradient
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100
120
140
160
Validation checks = 6 at the 167th epoch
Val fail
6
5
4
3
2
1
0
0
50
100
150

(c)


The best validation performance is 0.0068338 at the 161st epoch
Crossentropy
10^{0}
10^{-1}
10^{-2}
10^{-3}
Training
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Validation
Best
0
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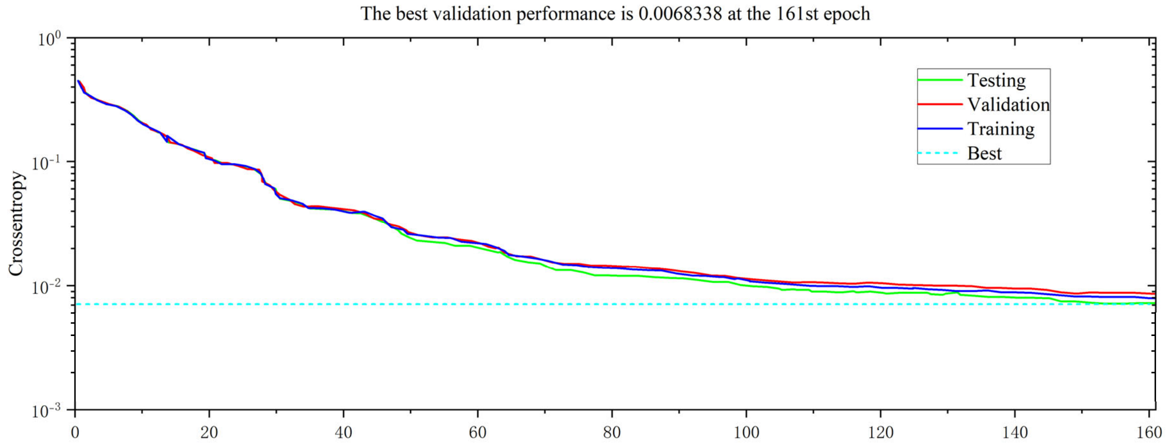


(d)

Fig. 8. Training results of back-propagation network: (a) Confusion Matrix; (b) ROC Curve; (c) Training State; (d) Performance Curve.

The detailed training results are presented in Table III.

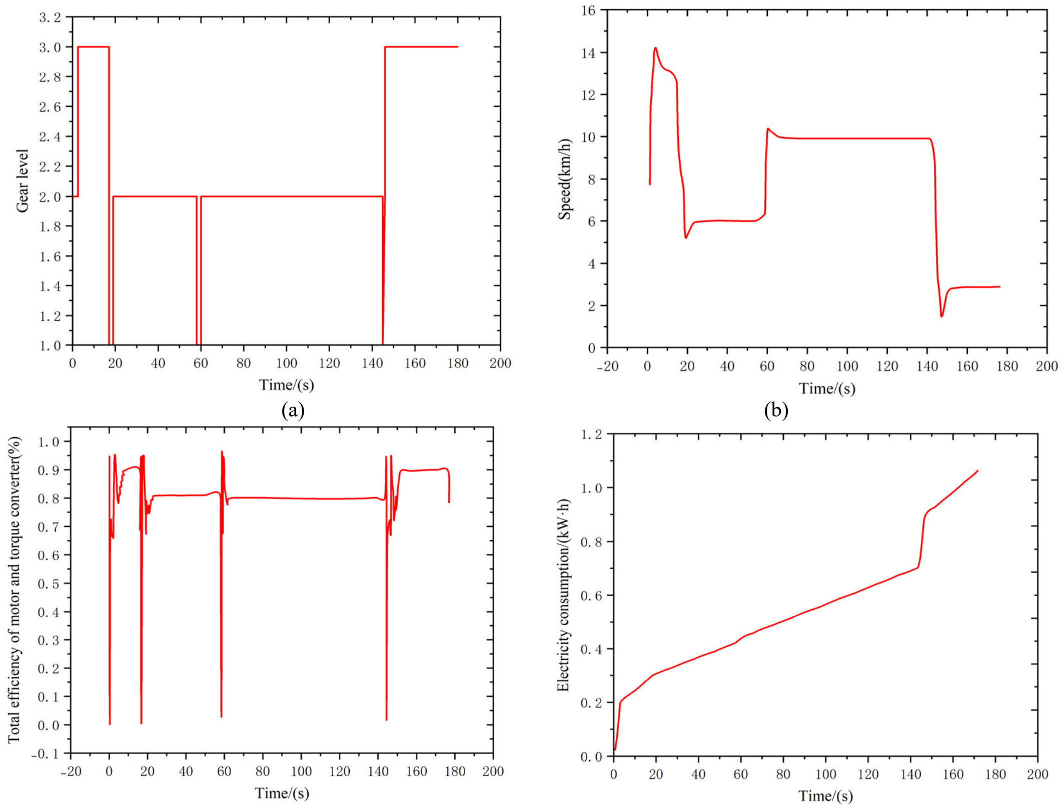
TABLE III. BACKPROPAGATION NEURAL NETWORK TRAINING RESULTS

Dataset	Observed value	Cross-Entropy	Error
Training	25734	0.0077	0.0081
Validation	5515	0.0068	0.0074
Testing	5515	0.0082	0.0091

From Fig. 8 and Table III, it is evident that the BPNN training achieved excellent performance, with cross-entropy errors below 1% in the training, validation, and testing phases. The performance verification curve indicates that the optimal validation performance occurred at the 161st training iteration, with a cross-entropy error of 0.0068338.

3) Simulation results and analysis

Using the developed simulation model, the proposed intelligent energy-saving gear-shifting control strategy is validated. The simulation step length corresponds to one typical operation cycle, which consists of a 150 m transportation distance. During simulation, it is assumed that the LHD operates on a flat surface and air resistance is ignored. The simulation results are presented in Fig. 9.



(a)

(b)

(c)

(d)

Fig. 9. Simulation results of a single work cycle for the LHD: (a) Gear Position; (b) Vehicle Speed; (c) Combined Efficiency of Motor and Hydraulic Torque Converter (d) Energy Consumption.

From the simulation results, the total duration of one operation cycle is 176.4 s. Analysis of Fig. 9(a) and (b) shows that the gear-shifting controller dynamically adjusts the transmission gear based on vehicle speed and actual operating conditions. During unloaded travel, the LHD operates in third gear, reaching this gear within approximately 4 s. During full-load travel, the LHD shifts to second gear, reaching this gear within approximately 5 s. During bucket loading operations, the LHD correctly shifts to first gear. From Fig. 9(c), it can be observed that throughout the operation cycle, the combined efficiency of the motor and hydraulic torque converter remains above 70%. From Fig. 9(d), the total energy consumption per work cycle is 1.10 kWh, which represents a 12.7% reduction compared to the optimized parameter case (1.26 kWh) without energy-saving shifting control. These results indicate that the proposed energy-saving gear-shifting strategy enables the LHD to quickly transition to higher gears, resulting in significant energy savings.

The simulation results confirm that an intelligent gear-shifting strategy, using motor speed, vehicle speed, and accelerator pedal position as control parameters, can dynamically adjust the gear position based on real-time operating conditions. This ensures that the motor and hydraulic torque converter operate within a high-efficiency range.

Furthermore, the proposed gear-shifting strategy, based on Backpropagation Neural Network (BPNN) control, has been successfully validated. Compared to non-energy-saving shifting strategies, the proposed strategy reduces per-cycle energy consumption by 12.7%, while maintaining the motor and torque converter efficiency between 70% and 90%.

V. CONCLUSION

This study focuses on the energy-saving optimization of battery-powered underground Load-Haul-Dump (LHD) machines, proposing an energy-saving strategy based on dual-motor drive and intelligent gear-shifting control. Through system modeling, optimization, and simulation analysis, the research results demonstrate that this method effectively improves energy utilization efficiency, reduces energy consumption, and enhances operational performance. The main conclusions are as follows:

1. Transmission system optimization improves energy efficiency:
   A drive system energy consumption model for LHDs was established, and an Adaptive Genetic Algorithm (AGA) was used to optimize the transmission ratio, resulting in a 9.4% reduction in energy consumption per work cycle. This optimization improved the energy conversion efficiency of the motor and reduced unnecessary energy losses.
2. Intelligent gear-shifting control effectively reduces energy consumption:
   An intelligent energy-saving gear-shifting strategy based on a Backpropagation Neural Network (BPNN) was proposed, enabling optimized gear-shifting control to ensure that the motor and hydraulic torque converter always operate in high-efficiency zones. Simulation results indicate that this gear-shifting strategy reduces energy consumption per work cycle by 12.7%, significantly improving the economic efficiency and operational performance of the LHD.
3. Feasibility of the energy-saving optimization strategy:
   The proposed energy-saving control strategy integrates mathematical modeling, optimization algorithms, and intelligent control methods. Simulation results confirm that this strategy significantly enhances the battery-powered LHD's operational duration, providing a new research approach and technical solution for energy-saving optimization in mining machinery.
4. Practical implications and industrial value:
   The proposed dual motor drive and intelligent gear-shifting control strategy offer clear practical implications for industry implementation. Existing LHD equipment can be retrofitted economically, benefiting from lower energy costs, extended equipment life, and reduced maintenance demands. The implementation pathway includes feasibility analysis, prototype testing, pilot projects in actual mining environments, and eventual full-scale deployment supported by operator training. This approach not only enhances operational efficiency and safety but also demonstrates scalability across various underground mining equipment types, thereby substantially strengthening its real-world applicability and industrial value.

Despite the promising results obtained in transmission system optimization and intelligent gear-shifting control, this study still has the following limitations:

1. Model simplifications and potential biases:
   The energy consumption model and simulation used in this study incorporate several simplifying assumptions to streamline analysis, such as ignoring air resistance and assuming negligible road gradients. These simplifications, while helpful for theoretical clarity, could lead to underestimations of energy consumption in more complex real-world scenarios. Therefore, actual operational energy consumption might deviate from the simulated results due to environmental variations and unexpected operational conditions.
2. Lack of experimental validation:
   This study primarily relies on mathematical modeling and simulation analysis, without conducting physical experiments on actual LHD equipment. Future work should focus on real-world testing under actual underground mining conditions to validate the effectiveness of the proposed optimization strategy while considering environmental factors affecting energy-saving control.
3. Adaptability of the intelligent control strategy:
   The proposed BPNN-based gear-shifting control

was trained using simulation-generated data and did not fully account for complex terrains (e.g., slopes, variable road conditions). Future research can integrate machine learning and online optimization techniques to enhance the intelligence and adaptability of the gear-shifting strategy.

4. Economic and technical constraints for implementation:
   Practical deployment of the proposed dual motor drive and intelligent gear-shifting strategy may face several economic and technical constraints. Initial retrofitting costs, availability of suitable hardware components, maintenance complexity, and training of operational personnel could pose challenges to widespread adoption. Future research must evaluate cost-effectiveness comprehensively and develop clear guidelines and roadmaps for cost-efficient integration into existing mining operations.
5. Broader applicability and future extension:
   The proposed energy-saving optimization strategy is developed and validated using a 3 m³ battery-powered underground Load-Haul-Dump (LHD) operating in a typical "L"-shaped route under standard tunnel conditions. While this scenario is representative of many underground mining operations, it does not capture the full diversity of LHD use cases, such as variable tunnel gradients, irregular operational routes (e.g., "T" or "V" patterns), and different machine scales or payload configurations. To enhance the generalizability of the findings, future work will incorporate a wider variety of operational scenarios and vehicle types. This includes extending the control strategy to LHDs with different bucket capacities, battery configurations, and operating speeds. Moreover, the methodology can be applied to simulate diverse tunnel geometries and environmental factors (e.g., temperature, humidity, road friction).

Overall, this study provides theoretical support and technical guidance for the energy-saving optimization of battery-powered LHDs. Future work will focus on experimental validation, intelligent control enhancements, and performing sensitivity analyses considering diverse operational conditions, operator behavior, and environmental factors. By addressing these limitations explicitly, future research will significantly enhance the applicability and credibility of energy-saving optimization strategies for battery-powered LHD machines in practical mining operations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

C.L. conducted the research, performed the data analysis, and drafted the manuscript. S.H. supervised the research direction, guided the overall research process, and provided constructive feedback and revisions to improve the quality of the manuscript; all authors had approved the final version.

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