Design and Implementation of a Computer-Aided Scaffolded Teaching Mode for Automotive Electrical Systems Curriculum

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Abstract. To address the limitations of traditional teaching methods for diesel vehicle electrical systems, this study proposes an integrated teaching model combining three-dimensional dynamic simulation with scaffolded instruction. A 24V diesel vehicle electrical system simulation model library was developed, enabling visual current-path tracking and interactive exploration across five major systems alongside phased instructional scaffolds. Controlled experiments demonstrated that students using this model achieved significantly higher scores in theoretical, practical, and comprehensive assessments compared to traditional instruction, with average improvements exceeding 6%. Over 85% of students reported enhanced understanding, and peer teachers provided positive evaluations. The findings indicate that this model effectively reduces cognitive load, improves instructional safety and effectiveness, and offers a feasible digital approach for automotive electrical curriculum reform.

Keywords: Diesel vehicle electrical systems; scaffolded instruction; three-dimensional simulation; current path visualization; vocational education

1 Introduction

The teaching of diesel vehicle electrical systems faces significant challenges due to theoretical abstraction and operational hazards. Traditional instruction relies heavily on two-dimensional circuit diagrams and static demonstrations, which inadequately convey complex concepts such as current-flow pathways, electromagnetic control logic, and multi-system coordination. This approach results in cognitive barriers for students attempting to grasp parallel-circuit attenuation and system interactions [1].

Three principal limitations characterize conventional methods. First, abstract circuit symbols hinder the formation of coherent mental models. Second, hands-on training presents safety risks, including electrical arcing and high current exposure. Third, the

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high cost of equipment restricts scalable, repeatable practical training. As automotive technology advances toward greater electrification and intelligence, there is an urgent need for pedagogical innovation that enhances system-thinking and diagnostic competencies [2,3].

Scaffolded instruction, based on Vygotsky's "zone of proximal development," provides a structured framework for supporting learner progression. While effective in engineering education, its application in automotive electrical training remains limited, often focused on procedural skills rather than deep conceptual understanding integrated with visualization technologies [4].

Three-dimensional simulation has been adopted primarily for teaching mechanical systems such as engines and chassis. Research on electrical system simulation remains underdeveloped, with most studies limited to static, partial models of 12V passenger vehicles. There is a notable absence of dynamic, system-wide 3D simulations for 24V diesel architectures, particularly those enabling real-time current-path tracking and multi-system visualization. Moreover, existing work often prioritizes technical implementation over pedagogical design and lacks rigorous experimental validation of instructional effectiveness [5,6].

This study addresses these gaps by developing and evaluating an integrated teaching model that combines 3D dynamic simulation with scaffolded instruction. The research objectives include: (1) creating a comprehensive 3D simulation model library covering core diesel vehicle systems; (2) implementing interactive current-path visualization; (3) designing a layered scaffolded teaching framework; and (4) conducting a controlled experiment to assess learning outcomes, student feedback, and peer evaluation.

The contributions are threefold: establishing the first full-system 3D simulation resource for 24V diesel electrical systems; proposing a visual inquiry-based teaching method centered on current-path tracking; and providing empirical evidence through a controlled experiment to support the effectiveness of digital scaffolded instruction in complex system training.

2 Core Concepts and Theoretical Foundation

2.1 Layered Design Principles of Scaffolded Teaching

The scaffolded teaching model is grounded in Vygotsky's "zone of proximal development" theory44. In diesel vehicle electrical systems instruction, this is implemented through a dual-track scaffold system comprising cognitive and operational components5,65,6. The cognitive scaffold follows a progressive path from component identification to system mastery, utilizing 3D visualization to transform abstract circuit principles into comprehensible units. The operational scaffold employs a "virtual simulation first, real operation follow-up" approach, ensuring safe skill transfer while mitigating risks associated with high-current systems.

2.2 Teaching Characteristics of Diesel Vehicle Electrical Systems

Instruction must address the distinctive features of 24V diesel systems compared to passenger vehicles. Key differences include voltage-specific circuit characteristics, high-current starting paths, and specialized glow-plug control systems. Traditional teaching methods struggle to visually demonstrate these concepts, particularly electromagnetic switching processes and multi-parameter control logic. 3D simulation enables safe visualization of these complex phenomena while illustrating system interrelationships and fault propagation paths essential for developing comprehensive diagnostic skills.

2.3 Educational Psychology Foundation of Three-Dimensional Simulation

The model integrates three educational psychology theories: dual-coding theory (verbal-visual integration enhances comprehension) [7], situated cognition (simulated environments support knowledge transfer), and cognitive load theory (scaffolds optimize cognitive allocation) [8]. Together, they provide a theoretical foundation for using 3D simulation to transform abstract principles into intuitive learning experiences.

3 Design and Implementation of Three-Dimensional Simulation Teaching System

3.1 Overall System Architecture Design

The three-dimensional dynamic simulation teaching system developed in this study employs a modular architecture[9], designed to balance pedagogical functionality with technical implementation in accordance with the characteristics of vocational education. As shown in Figure 1, the system comprises a complete technical framework consisting of four layers: data, model, logic, and interaction, ensuring stable operation and a positive user experience for various teaching functions.

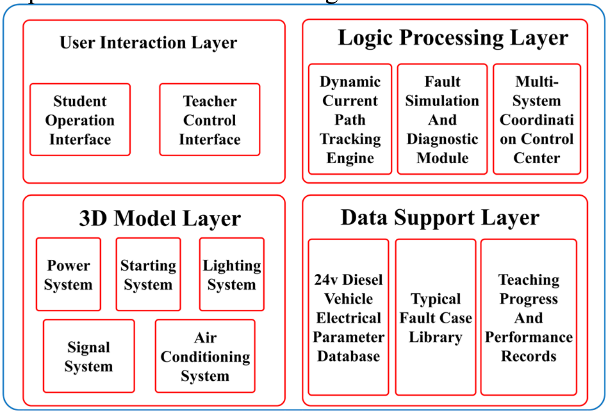

Fig. 1. Schematic Diagram of the Three-Dimensional Dynamic Simulation Teaching System Architecture

The data layer stores comprehensive technical parameters of the 24V diesel vehicle electrical system, including key data such as component specifications, circuit resistance, and operating current ranges, providing accurate foundational data support for simulation calculations. The model layer establishes detailed three-dimensional models of the five major systems, with each model encompassing three data dimensions: geometric information, electrical properties, and connection relationships. The logic layer serves as the core of the system, responsible for processing key teaching functions such as current calculation, fault simulation, and system linkage. The interaction layer offers an intuitive user interface tailored to meet the respective needs of student learning and teacher control.

The system was developed using Unity3D as the core platform, with 3D models constructed in SolidWorks and electrical behavior simulated via MATLAB/Simulink co-simulation. Model accuracy adheres to real vehicle electrical schematics, with component tolerances within ±5%. The system operates smoothly on standard educational computers (Intel i5, 8GB RAM), ensuring accessibility for most vocational institutions.

3.2 Implementation of Key Teaching Functions

Dynamic Current Path Tracking Function.

The system realizes visualized tracking of current paths across the entire vehicle electrical system, representing a core innovation[10]. For the power system, it animates the complete current flow from the positive battery terminal to various loads via the main fuse and distribution units. During parallel circuit demonstrations, it clearly visualizes current distribution across branches, aiding comprehension of current attenuation principles.

In starting system instruction, a dual-path comparison function simultaneously displays the low-current preheating process of glow plugs and the high-current starter circuit operation. Visual distinctions in color and flow rate help differentiate these paths, addressing the pedagogical challenge of illustrating high-current flow.

For signal systems, the system tracks control logic—such as for turn signals and brake lights—showing the full signal transmission chain from switch activation to lamp illumination. Interactive switch operation allows students to observe real-time path changes, deepening their understanding of signal system principles.

Fault Simulation and Diagnostic Training.

The system includes a fault case library for diagnostic training. Instructors can select or customize faults, and students diagnose them using virtual tools (multimeter, test light) that simulate real instruments[11]. Table 1 shows the main fault types and instructional purposes.

Table 1. Correspondence between Fault Simulation Types and Instructional Objectives

Fault Type	System Involved	Teaching Objective	Difficulty Level
Wire Break	Whole System	Master the method for circuit continuity testing	Beginner

Poor Grounding	Lighting System	Understand the impact of grounding quality on the system	Beginner
Relay Failure	Starting System	Master the testing and replacement of relays	Intermediate
Control Module Fault	Air Conditioning System	Understand the principles of electronic control	Advanced
Multi-System Related Fault	Linkage System	Develop comprehensive diagnostic capabilities	Advanced

Multi-System Linkage Demonstration.

Complex interactions exist among the subsystems of diesel vehicle electrical systems, which are challenging to visualize through conventional teaching methods. This system implements a multi-system linkage demonstration function, particularly during vehicle startup, where it synchronously displays the coordinated operation of the power supply system, starting system, glow plug system, and instrument system. Students can observe real-time changes in current, voltage fluctuations, and signal transmission processes across systems during startup, thereby establishing cognitive associations among different systems.

The electrical correlation between the air conditioning system and engine load represents a challenging teaching topic. The system demonstrates changes in engine load upon air conditioning compressor activation through dynamic parameter adjustments, along with subsequent adjustments in the charging system's operating status. This cross-system correlation demonstration helps students comprehend the holistic and dynamic balance principles of automotive electrical systems.

4 Construction of Scaffolded Teaching Mode Based on Simulation System

4.1 Design of the Overall Teaching Mode Framework

This three-stage scaffolded teaching model, anchored by the 3D dynamic simulation system, follows the logic of “virtual cognition → practice transfer → comprehensive application” (see Figure 2).

In the pre-class phase, scaffolding focuses on activating prior knowledge and reducing cognitive load through guided animations and structured previews. During class, support shifts to guiding deep inquiry and providing cognitive tools, as students interact with the simulation in progressive task chains to build knowledge of current paths and control logic. In the post-class phase, the scaffold evolves to support skill transfer and consolidate knowledge structures through virtual fault diagnosis, enabling the critical transition from “knowing” to “applying.” Throughout, the model embodies the principle of fading support: teacher-provided scaffolding gradually recedes as students’ independent inquiry expands, all within a safe, digitally-enhanced learning environment.

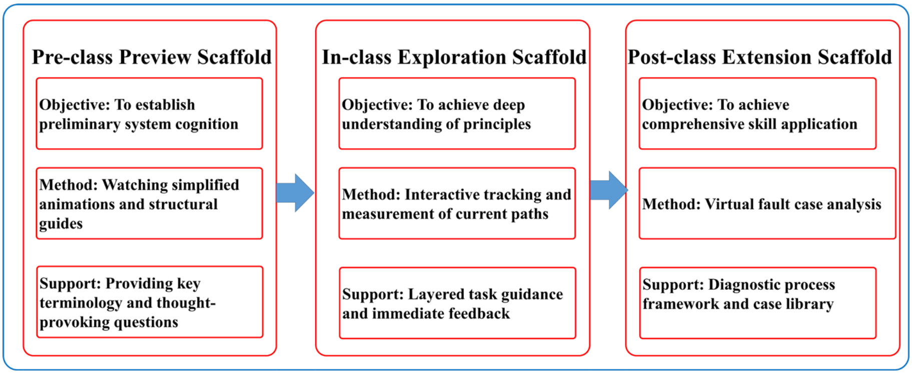

Fig. 2. Overall Framework of the Scaffolded Teaching Mode

4.2 Specific Scaffolding Design for the Five Major Systems

Based on the unique teaching characteristics of the five major electrical systems in diesel vehicles, this study designed targeted hierarchical teaching scaffolds, as shown in Table 2. These scaffold designs adhere to the cognitive progression from specific to abstract and from local to global, outlining a clear pathway for advancing abilities in each system.

Table 2. Hierarchical Teaching Scaffold Design for the Five Major Systems

Target System	First-Layer Scaffold (Cognitive Foundation)	Second-Layer Scaffold (Principle Exploration)	Third-Layer Scaffold (Comprehensive Application)
Power System	Identify differences between 24V and 12V components	Trace the main path from "battery → electrical appliance"	Analyze power distribution logic under multiple simultaneous loads
Starting System	Recognize high-current path components	Visualize the working process of the electromagnetic switch	Diagnose faults related to weak starting
Lighting System	Distinguish parallel circuit layouts	Demonstrate current distribution between low/high beams	Troubleshoot dimming or flickering lights
Signal System	Identify signal inputs and control units	Track signal flow from "switch → relay → load"	Diagnose logic control failures
Air Conditioning System	Recognize compressor control circuits	Analyze the relationship between temperature/pressure signals and control responses	Diagnose electrical causes of insufficient cooling

4.3 Teaching Implementation Process and Stage Division

The teaching process follows three stages: (1) System recognition: identifying components in 3D simulation; (2) Principle exploration: task-driven interaction with scaffolded guidance; (3) Comprehensive application: diagnosing multi-system faults to develop diagnostic thinking. This progression supports safe, coherent learning.

5 Teaching Experiment and Effectiveness Analysis

5.1 Experimental Design and Implementation

To scientifically evaluate the effectiveness of the proposed teaching model, a controlled teaching experiment was conducted in the Automotive Application and Maintenance program of a vocational college. The study involved two intact classes from consecutive academic years, randomly assigned as control and experimental groups. The control group (Class of 2024, $n = 32$) received traditional instruction, while the experimental group (Class of 2025, $n = 28$) used the scaffolded simulation-based mode. Random assignment was performed at the class level to avoid selection bias, and pre-test scores confirmed no significant prior knowledge differences ($p > 0.05$). The experiment strictly controlled for extraneous variables: the same instructor with over ten years of teaching experience taught both cohorts, using identical textbooks, syllabi, total instructional hours, and assessment standards for theoretical knowledge, practical skills, and comprehensive projects. The experimental period covered one full academic semester.

5.2 Three-Dimensional Effectiveness Evaluation

Comparative Analysis of Academic Performance.

After the experiment, learning outcomes were quantified across three dimensions: theoretical assessment, practical assessment, and comprehensive project evaluation. A comparison of the scores is shown in Table 3.

Statistical analysis indicated that the experimental group significantly outperformed the control group across all three dimensions. The improvements were particularly notable in the theoretical assessment, which required understanding circuit principles, and the practical assessment, which demanded analytical and judgment skills.

Table 3. Comparison of Academic Performance Between the Experimental and Control Groups

Assessment Dimension	Control Group Average Score	Experimental Group Average Score	Score Improvement
Theoretical Assessment	78.4	84.0	+5.6%
Practical Assessment	76.8	83.6	+6.8%
Comprehensive Project	77.2	83.4	+6.2%

Structured Analysis of Subjective Student Feedback.

Student subjective experiences were collected using a five-point Likert scale and open-ended questions. The survey instrument was adapted from the Technology Acceptance Model (TAM) and demonstrated good internal consistency (Cronbach's $\alpha = 0.87$). Quantitative analysis of Likert responses confirmed significant between-group differences ($p < 0.01$) across all dimensions, supporting the descriptive findings. As shown in Table 4, the experimental group received higher ratings across all experiential dimensions.

Table 4. Comparison of Subjective Feedback Survey Results

Evaluation Dimension	Specific Indicator	Control Group Approval Rate	Experimental Group Approval Rate	Difference Analysis
Learning Experience	Ease of understanding abstract principles	76%	87%	+11%
	Significant increase in learning interest	78%	91%	+13%
	Improvement in classroom participation	75%	89%	+14%
Skill Perception	Enhanced understanding of current paths	77%	90%	+13%
	Increased confidence in fault diagnosis	73%	86%	+13%
	Strengthened awareness of safe operations	82%	94%	+12%
Teaching Evaluation	Novelty and effectiveness of teaching method	80%	93%	+13%
	Willingness to continue using this mode	82%	95%	+13%

Qualitative analysis of in-depth interviews further revealed the learning mechanisms. Students in the experimental group commonly reported that "visualized current tracking made complex circuit principles intuitive and easier to understand" and that "repeated practice in the virtual environment helped establish solid diagnostic thinking." Notably, several students mentioned that "the scaffolded learning guidance allowed them to master system knowledge progressively, avoiding frustration during the learning process."

Feedback from the control group reflected a different learning experience. While most students expressed basic satisfaction with the traditional teaching method, they commonly reported "difficulty understanding circuit principles" and "psychological pressure during hands-on vehicle operations." This contrasts sharply with the learning confidence demonstrated by the experimental group.

Peer Review Results.

Three teachers with over three years of teaching experience were invited to evaluate the teaching method. As shown in Table 5, the peer experts provided positive feedback on the new teaching model from multiple dimensions.

Table 5. Summary of Peer Review Results

Evaluation Dimension	Key Points of Evaluation	Consensus Feedback from Three Instructors
Teaching Innovation	Degree of methodological innovation	Regarded "dynamic current path tracking" as a significant innovative breakthrough in circuit instruction.
Teaching Practicality	Effectiveness in solving practical teaching problems	Affirmed that it addressed the safety demonstration challenges of high-current circuits in diesel vehicles.
Technology Integration	Level of integration between information technology and teaching	Considered the combination of 3D simulation and scaffolded teaching theory to be close-knit and natural.
Scalability	Application prospects in other courses/institutions	Unanimously recognized its strong potential for promotion and planned to implement it in their respective classes.
Student Benefit	Contribution to enhancing students' abilities	Noted that it helps cultivate students' systems thinking and inquiry skills.

The peer teachers particularly emphasized: "This method transforms the traditional teaching challenges of 'unclear explanations, opaque concepts, and risky practice' into advantages of visualization, interactivity, and repeatability, providing a successful case for the digital reform of vocational education."

5.3 Comprehensive Discussion

Results validate the model's effectiveness. Success stems from: cognitive (visualization reduces load), skill (virtual training promotes transfer), and affective (safe environment enhances confidence) factors. The method suits high-risk, high-cost training scenarios.

Notably, the experimental group's advantages in understanding system interrelationships and diagnosing complex faults indicate that this model helps cultivate engineering systems thinking—a core competency for modern automotive maintenance professionals. The study also found that the model places higher demands on teachers' informatization teaching abilities, necessitating corresponding teacher training support.

A limitation of this study is its relatively small sample size and single institutional origin. Future research should involve larger sample validation across multiple institutions and explore the application of this model in more complex scenarios, such as high-voltage systems in new energy vehicles.

6 Conclusions and Prospects

This study developed and validated a scaffolded teaching model that integrates three-dimensional dynamic simulation to address the pedagogical challenges of abstract principles and operational risks in diesel vehicle electrical system instruction. Through the construction of a 24V diesel vehicle electrical system simulation resource library and a hierarchically designed teaching scaffold, the model establishes a progressive learning pathway from component cognition to system application. Experimental results indicate that the model significantly enhances students' theoretical understanding and practical skills, with average performance improvements exceeding 6% across all assessment dimensions, and has received highly positive evaluations from both students and instructors. The model's core value lies in providing a safe digital alternative for high-risk practical training and offering an operable reference for vocational education reform. In terms of implementation, the system can be deployed on existing computer labs in vocational schools, with no need for specialized hardware beyond standard PCs. Initial development costs are offset by long-term reductions in physical equipment maintenance and replacement, making it a cost-effective solution for resource-constrained settings.

Despite these achievements, the current study has limitations such as hardware dependency and constrained network experience. Future research could advance in three directions: promoting technological lightweight and mobile adaptation to improve accessibility; exploring the integration of immersive technologies like VR to enhance learning authenticity; and extending the model to cutting-edge fields such as high-voltage systems in new energy vehicles to validate its adaptability in more complex technological scenarios. As vehicle electrification accelerates, such digital teaching models will play an increasingly vital role in cultivating technical talents aligned with industrial needs.

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