Статья поступила в редакцию: 22.08.2026
Статья принята к публикации: 28.08.2026
Статья опубликована: 08.09.2026

УДК 621.317+378.147

DOI: 10.32743/UniPsy.2026.147.9.23354

The integration of digital technologies in the teaching of automotive electrical systems: experimental findings

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Интеграция цифровых технологий в преподавание автомобильных электрических систем: экспериментальные результаты

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Abstract

This study evaluates the pedagogical effectiveness of a digital technology-based teaching methodology for the course «Automotive Electrical Systems» in technical higher education institutions through a comprehensive pedagogical experiment. The relevance of the research is determined by the rapid advancement of automotive electronics, including electronic control systems, CAN and LIN communication protocols, intelligent sensors, electronic control units (ECUs), and the increasing prevalence of electric and hybrid vehicles. The experimental study was

Библиографическое описание: Рустамова Н.И., Сайдалиев И.Н. Интеграция цифровых технологий в преподавание автомобильных электрических систем: экспериментальные результаты // Universum: психология и образование : электрон. научн. журн. 2026. 9(147). URL: https://7universum.com/ru/psy/archive/item/23354

For citation: Rustamova N.I., Saydaliyev I.N. The integration of digital technologies in the teaching of automotive electrical systems: experimental findings // Universum: Psychology and Education : electronic scientific journal. 2026. No. 9(147). Available at: https://7universum.com/ru/psy/archive/item/23354

conducted between 2024 and 2026 involving 416 undergraduate students of Transport Engineering across Andijan State Technical Institute, Tashkent State Technical University, and Jizzakh Polytechnic Institute. The study was implemented in three stages: diagnostic, formative, and final evaluation. During the formative stage, a digital methodology integrating learning management systems (LMS), virtual laboratories, diagnostic simulators, and Project-Based Learning (PBL) was introduced. Statistical analysis via Student's t-test and Pearson's chi-square test demonstrated a 13.4 % increase in overall learning effectiveness and a 31.6 % improvement in practical diagnostic competencies within the experimental group.

Аннотация

В данном исследовании на основе комплексного педагогического эксперимента оценивается педагогическая эффективность методики обучения дисциплине «Электрические системы автомобилей» в технических высших учебных заведениях с использованием современных цифровых технологий. Актуальность работы обусловлена стремительным развитием автомобильной электроники, включая электронные системы управления, коммуникационные протоколы передач данных CAN и LIN, интеллектуальные датчики, электронные блоки управления (ECU), а также растущей популярностью электрических и гибридных транспортных средств. Экспериментальное исследование проводилось в 2024–2026 годах с участием 416 студентов бакалавриата направления «Транспортная инженерия» в трёх ведущих технических вузах Узбекистана: Андижанском государственном техническом институте, Ташкентском государственном техническом университете и Джизакском политехническом институте. Исследование было реализовано в три этапа: констатирующий, формирующий и контрольно-оценочный. В ходе эксперимента в учебный процесс была внедрена цифровая методика, интегрирующая системы управления обучением (LMS), виртуальные лаборатории, диагностические тренажеры-симуляторы и проектно-ориентированное обучение (PBL). Статистический анализ (t-критерий Стьюдента и критерий Пирсона χ^2) показал повышение общей эффективности обучения на 13,4 %, а также существенный рост практических диагностических навыков на 31,6 % в экспериментальной группе.

Keywords: Automotive Electrical Systems, digital education, pedagogical experiment, electronic learning resources, virtual laboratory, professional competence, STEM education, automotive diagnostics, interactive learning, engineering education.

Ключевые слова: электрические системы автомобилей, цифровое образование, педагогический эксперимент, электронные образовательные ресурсы, виртуальная лаборатория, профессиональная компетенция, STEM-образование, автомобильная диагностика, интерактивное обучение, инженерное образование.

1. Introduction

Modern vehicles have transformed into complex cyber-physical systems packed with electronic control units (ECUs), smart sensors, and high-speed networks [1, 2]. Developing these practical engineering competencies requires moving beyond standard classrooms to integrate virtual labs, interactive simulations, and applied problem-solving tools [3]. Numerous international studies have demonstrated that active and digital learning environments significantly enhance students' academic achievement and professional competence in engineering disciplines [4].

As a result, engineering universities face the urgent need to prepare graduates for increasingly complex technical environments. Purely theoretical, lecture-based methods can no longer build the hands-on diagnostic skills modern automotive industries demand. Today's automotive specialists need expertise spanning traditional wiring, ECU operation, CAN/LIN communication protocols, high-voltage systems, and onboard diagnostics. Developing these practical engineering competencies requires moving beyond standard classrooms to integrate virtual labs, interactive simulations, and applied problem-solving tools.

International trends in engineering education increasingly emphasize competency-based learning, Project-Based Learning (PBL), Blended Learning, digital learning environments, and learner-centered instructional design. These pedagogical approaches enable students to integrate theoretical knowledge with practical engineering applications while simultaneously developing critical thinking, independent decision-making, collaborative problem-solving, and professional communication skills. Numerous international studies have demonstrated that digital learning environments significantly enhance students' academic achievement, motivation, and professional competence in engineering disciplines.

In Uzbekistan, digitalizing higher education and aligning engineering curricula with international standards are key national priorities. While these reforms support pedagogical innovation, teaching the Automotive Electrical Systems course still faces notable hurdles. Instruction remains largely lecture-based, while access to virtual labs, modern diagnostic equipment, and high-quality digital learning resources remains constrained. As a result, graduates frequently lack the hands-on diagnostic competence required to maintain modern electronically controlled vehicle systems. The central research hypothesis of this study proposes that the systematic implementation of a competency-based instructional methodology supported by digital educational technologies, virtual laboratories, interactive simulations, and intelligent learning resources will significantly improve students' theoretical understanding, practical skills, and professional competencies in automotive electrical systems.

2. Materials and Methods

This study employed a quasi-experimental research design to evaluate the pedagogical effectiveness of a digital technology-based teaching methodology for the Automotive Electrical Systems course. A mixed-method research approach was adopted, integrating pedagogical observation, questionnaire surveys, diagnostic testing, practical performance assessment, expert evaluation, comparative analysis, and mathematical-statistical methods. The research methodology was developed in accordance with internationally recognized experimental research principles widely applied in engineering and educational sciences to assess instructional effectiveness [5].

The experimental study was conducted during 2024–2026 across three technical universities in Uzbekistan: Andijan State Technical Institute, Tashkent State Technical University, and Jizzakh Polytechnic Institute. A total of 416 Transport Engineering undergraduates participated, divided into an experimental group (n = 209) and a control group (n = 207). Group allocation was based on prior academic performance and initial diagnostic assessments, ensuring baseline statistical equivalence ($p > 0.05$) to support internal validity.

In contrast, the control group followed the traditional curriculum covering identical academic content. Achievements were evaluated using competency-based criteria across theoretical knowledge and practical diagnostic skills. Performance data analyzed via Student's t-test and Pearson's chi^2 test ($p < 0.05$) confirmed that the digital methodology significantly enhanced both theoretical understanding and practical automotive diagnostic skills while maintaining data confidentiality through anonymized identification codes.

3. Results

The findings of the pedagogical experiment were comprehensively analyzed to evaluate the effectiveness of the proposed digital technology-based teaching methodology. Baseline diagnostic assessment results showed no statistically significant differences between the experimental and control groups, confirming comparable initial academic preparedness ($p > 0.05$) and establishing internal validity prior to the intervention.

The initial assessment revealed that 9.6 % of students in the experimental group achieved an excellent performance level compared with 6.8 % in the control group. Similarly, the proportion of students demonstrating unsatisfactory performance was 33.0 % and 35.3 %, respectively. Statistical analysis indicated that these differences were not significant ($p > 0.05$), confirming that the two groups were academically equivalent at the beginning of the experiment.

Upon completion of one academic semester, students' academic achievement and professional competencies were reassessed using the same evaluation criteria employed during the initial diagnostic stage.

Table 1.

Final Results of the Pedagogical Experiment

Group	Excellent	Good	Satisfactory	Unsatisfactory
Experimental (n = 209)	54	63	69	23
Control (n = 207)	19	54	99	35

Post-intervention results demonstrated substantial academic gains in the experimental group, with excellent performances increasing from 20 to 54 students and unsatisfactory outcomes dropping from 69 to 23. In contrast, the control group exhibited only modest improvements. Students exposed to the digital methodology showed marked advancement in circuit analysis, ECU operation, and fault diagnosis, largely driven by high practical engagement with virtual laboratories and interactive simulation tools.

Table 2.

Development of Students' Professional Competencies (%)

Competency	Experimental Group	Control Group
Theoretical knowledge	+23.4	+4.6
Electrical circuit analysis	+27.8	+5.2

Competency	Experimental Group	Control Group
Diagnostic skills	+31.6	+6.3
Engineering problem-solving	+25.2	+4.8
Professional communication	+21.9	+3.9

As shown in Table 2, the proposed methodology generated major gains across all competencies. Diagnostic skills saw the largest impact, improving by 31.6 % in the experimental group versus 6.3 % in the control group. Strong gains were also recorded in circuit analysis, problem-solving, and theoretical knowledge, proving that virtual labs and interactive simulations effectively bridge theory and real-world engineering practice.

The statistical analysis demonstrated that the proposed methodology increased overall learning effectiveness by 13.4 %. This improvement was reflected in both theoretical knowledge and practical competencies, confirming that integrating digital educational technologies significantly enhances modern automotive engineering education.

4. Discussion

The systematic integration of digital technologies into the Automotive Electrical Systems course significantly enhances learning outcomes, bridging the gap between theoretical knowledge and practical engineering demands. Modern vehicles—equipped with advanced electronic control units, complex communication networks, and diagnostic algorithms—require competencies in analytical reasoning, fault diagnosis, and problem-solving. Incorporating virtual laboratories, interactive simulations, and digital diagnostic models creates authentic learning environments that align with competency-based engineering education frameworks [6, 7]. These findings corroborate established literature showing that experiential learning, cognitive problem-solving, and active STEM education substantially improve professional readiness, critical thinking, and technical competencies [8, 9, 10].

5.Conclusion

The findings of this study demonstrate that the proposed digital technology-based teaching methodology for the Automotive Electrical Systems course significantly enhances students' theoretical knowledge, practical skills, and professional competencies. The integration of virtual laboratories, interactive simulations, electronic learning resources, and problem-based learning created a more effective and practice-oriented learning environment.

Statistical analysis using Student's t-test and Pearson's χ^2 test confirmed that the observed improvements were statistically significant ($p < 0.05$). The implementation of the proposed methodology increased overall learning effectiveness by 13.4 %, confirming its educational value and practical applicability.

Overall, the results indicate that systematic integration of digital pedagogical technologies can substantially improve the quality of engineering education and contribute to the preparation of highly qualified automotive engineers capable of meeting the demands of the modern automotive industry.

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