Enhancing Automotive Vocational Skills through Augmented Reality: A Case Study on Front-wheel Drive Powertrain Learning

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***Abstract*—This study examined the effectiveness of Augmented Reality (AR) as an instructional medium for enhancing technical skills in automotive vocational education, with a focus on Front-Wheel Drive (FWD) powertrain learning. A quantitative research design based on the Unified Theory of Acceptance and Use of Technology (UTAUT) was employed to examine technology acceptance and its relationship with skill enhancement. Data were collected from 164 automotive engineering students through questionnaires measuring Performance Expectancy, Effort Expectancy, Behavioral Intention, and Skill Enhancement. In addition, objective rubric-based practical assessments involving 30 students were conducted to compare learning outcomes between an AR-based experimental group and a conventional control group. The results indicated that Performance Expectancy and Effort Expectancy significantly influenced Behavioral Intention, which in turn strongly predicted skill enhancement. Students in the AR group also demonstrated higher practical performance scores compared with those in the conventional learning group. Overall, the findings indicate that AR-supported learning can effectively enhance automotive engineering students' practical skills in automotive powertrain education.**

***Keywords*—augmented reality, front-wheel drive powertrain, skill enhancement, vocational education, engineering education**

I. Introduction

Augmented Reality (AR) has increasingly been recognized as a transformative educational technology, particularly in learning contexts that require three-dimensional visualization, procedural understanding, and practice-oriented activities. A growing body of literature suggests that AR supports immersive and interactive learning environments that can enhance student engagement, motivation, and higher-order cognitive skills, including spatial ability and problem-solving [1–6]. In Science, Technology, Engineering, and Mathematics (STEM) education, AR has been shown to facilitate conceptual understanding by allowing learners to visualize and manipulate abstract or complex objects that are otherwise difficult to comprehend through conventional two-dimensional media [7–9]. These characteristics make AR particularly relevant for vocational education, where learning outcomes emphasize applied knowledge, technical competence, and alignment with real-world practices [10].

Within vocational and technical education, particularly in automotive training, AR has shown strong potential to bridge the persistent gap between theoretical instruction and hands-on practice. Previous studies indicate that AR-based learning environments can improve students' technical performance, spatial visualization, and understanding of mechanical systems by providing interactive simulations of real automotive components and processes [11–14]. Through dynamic visualization of engines, powertrains, and drivetrain systems, AR enables learners to observe component interactions, torque transmission, and operational sequences in a safe, repeatable, and resource-efficient manner. These affordances are especially valuable in automotive education, where access to physical training equipment is often constrained by cost, safety risks, limited availability, and maintenance requirements.

Despite these promising developments, conventional instructional approaches in Front-Wheel Drive (FWD) powertrain learning still rely heavily on static two-dimensional diagrams, sectional drawings, and limited physical demonstrations. Such representations are often insufficient to convey the spatial integration between the engine, clutch (or torque converter), transaxle assembly, differential gears, and drive shafts within a compact FWD configuration. The complexity of integrated transmission–differential mechanisms, multidirectional torque flow paths, and fault diagnosis procedures makes it difficult for students to develop accurate mental models of system behavior through flat visualization alone [15].

Despite these promising developments, existing AR applications in vocational automotive education continue to exhibit several critical limitations. Many studies focus primarily on generic mechanical visualization without sufficient alignment to specific curricular learning outcomes or industry-referenced competency standards. In particular, empirical research addressing AR-based learning for FWD powertrain systems remains scarce, even though FWD configurations dominate contemporary passenger vehicles. Essential competencies such as torque flow analysis, differential operation, systematic fault diagnosis, and task-based procedural assessment are frequently underrepresented in current AR learning tools. Moreover, the integration of industry-aligned frameworks, such as those referencing Automotive Service Excellence (ASE) competency standards, is rarely incorporated into AR design and evaluation, resulting in a misalignment between educational innovation and workplace skill requirements.

Another important trend in AR-enhanced education is the rapid expansion of mobile-based AR platforms. Smartphones and tablets offer flexible, accessible, and cost-effective alternatives to high-end AR hardware, thereby enabling broader adoption across diverse vocational education [16–19]. Mobile AR facilitates learning beyond the classroom environment and supports self-directed, anytime, anywhere learning. Prior studies have also shown that the integration of AR with established digital learning tools can strengthen conceptual understanding and learner engagement by making abstract technical content more tangible and interactive [20]. Nevertheless, rigorous empirical evidence examining the effectiveness of mobile-based AR in developing measurable vocational automotive competencies, particularly objective technical skills assessed through performance-based rubrics, remains limited.

Furthermore, while a substantial body of research has investigated user acceptance of AR using models such as the Unified Theory of Acceptance and Use of Technology (UTAUT), most studies focus on perceptual constructs such as perceived usefulness, ease of use, and behavioral intention without directly linking these to measurable technical performance outcomes [21]. There remains limited empirical evidence connecting technology acceptance variables directly to objective skill acquisition in vocational training contexts, representing a significant research gap.

Beyond pedagogical and technological considerations, several contextual challenges continue to constrain the effective implementation of AR in vocational education. These include inadequate technological infrastructure, variations in device compatibility, limited institutional support, and insufficient teacher readiness to integrate immersive technologies into instructional practice [22, 23]. In addition, learner experience factors, encompassing cognitive load, emotional engagement, and usability, have been identified as critical determinants of AR learning effectiveness. Design-oriented approaches such as Kansei Engineering have been proposed to optimize AR interfaces by aligning functional performance with affective user responses, thereby sustaining motivation and improving learning outcomes [24]. However, systematic incorporation of these design considerations into vocational AR applications, particularly within automotive training, remains underexplored.

Addressing these gaps is important from both theoretical and practical perspectives. Theoretically, research that integrates AR technology, vocational pedagogy, and industry-aligned competency assessment can advance understanding of how immersive learning environments support procedural knowledge acquisition and technical skill development. Practically, the development of accessible, curriculum-aligned, and industry-relevant AR learning tools has the potential to enhance the quality of vocational training, improve student preparedness for the automotive workforce, and reduce reliance on costly physical training equipment.

Accordingly, this study not only evaluates the effectiveness of mobile-based AR in supporting FWD powertrain learning but also bridges the gap between technology acceptance and objective skill performance by integrating UTAUT-based acceptance analysis with rubric-based assessment of authentic technical competencies.

Based on this background, the present study aims to evaluate the effectiveness of mobile-based AR in enhancing automotive engineering students' technical skills, spatial visualization, and problem-solving abilities in learning FWD powertrain systems. In addition, this study examines user acceptance and implementation challenges related to device compatibility and instructional readiness. By integrating technology acceptance analysis with objective, rubric-based skill assessment and industry-referenced learning objectives, this research provides empirical evidence and practical recommendations for the meaningful integration of AR into vocational automotive education.

II. Literature Review

A. Augmented Reality in Vocational Education

Augmented Reality (AR) has increasingly been positioned as a powerful instructional technology in vocational education and training due to its ability to seamlessly integrate digital information with real-world environments in real time. Unlike conventional digital learning media, AR allows learners to observe, manipulate, and interact with three-dimensional representations of tools, components, and procedures, thereby supporting experiential, situated, and practice-oriented learning [25, 26].

In Technical and Vocational Education and Training (TVET), AR is increasingly applied not only as a visualization tool but also as a medium for procedural training, equipment familiarization, and simulation of workplace tasks. This shift reflects the pedagogical orientation of vocational education, where learning outcomes emphasize the integration of conceptual understanding with psychomotor competence and industry-relevant skills. Research on professional and technical training indicates that AR environments allow learners to practice complex operations in safe and repeatable conditions, particularly when access to real equipment is limited or costly [15, 27].

Recent empirical studies consistently report that AR enhances conceptual understanding and practical skill acquisition, particularly in learning situations involving complex spatial relationships, system interdependencies, and procedural sequences [28–30]. More recent meta-analytic evidence further confirms that AR can significantly improve learning performance, spatial reasoning, and task-based outcomes in science, engineering, and technical education contexts where learners must interpret dynamic mechanical relationships and procedural workflows [31–33]. These affordances are highly relevant in vocational contexts, where educational outcomes emphasize not only cognitive understanding but also psychomotor competence, procedural accuracy, and workplace readiness.

Evidence from systematic reviews and meta-analyses further substantiates the effectiveness of AR in vocational education. Radianti *et al*. [27] reported that AR-based learning environments positively influence cognitive, affective, and behavioral outcomes, with notable improvements in task performance, learner motivation, and engagement. More recent reviews focusing on professional and engineering education similarly highlight that immersive technologies such as AR enable authentic task simulation and situated learning experiences that closely mirror real industrial workflows [15, 33, 34]. A key pedagogical advantage identified across these studies is AR's capacity to visualize hidden components and dynamic processes-features that are often difficult to convey using static diagrams or text-based instruction alone [34, 35].

Despite these benefits, the literature also reveals several limitations in current AR implementations within vocational education. Many existing studies remain exploratory in nature, emphasizing usability testing, learner satisfaction, or short-term learning outcomes rather than sustained skill development and competency mastery. Furthermore, a number of AR studies in TVET focus on general technology demonstrations rather than domain-specific applications aligned with occupational standards or competency-based curricula [32]. Moreover, AR applications are frequently designed as generic instructional tools without explicit alignment to specific vocational curricula or industry-referenced competency standards. In technically intensive fields such as automotive education, this limitation becomes particularly pronounced. Although automotive systems are inherently spatial and procedural, research focusing on AR-supported learning for specific subsystems, such as Front-Wheel Drive (FWD) powertrain mechanisms, remains limited. Consequently, there is a clear need for domain-specific AR applications that support authentic vocational tasks and competency-based assessment frameworks.

B. Mobile Augmented Reality Adoption in Education

Advances in mobile computing technologies have significantly accelerated the adoption of AR in educational settings. Mobile Augmented Reality (MAR), delivered through smartphones and tablets, provides a cost-effective, scalable, and accessible alternative to head-mounted displays and specialized AR hardware. Prior studies emphasize that MAR reduces institutional and financial barriers to adoption while offering flexible learning opportunities that extend beyond conventional classroom environments [36–38].

The widespread availability of smartphones has made mobile AR particularly attractive for vocational education institutions, where access to advanced laboratory equipment and immersive technologies may be limited. By leveraging students' personal mobile devices, MAR enables scalable deployment of interactive instructional media without requiring substantial infrastructure investment, thereby supporting flexible and self-directed learning in technical education contexts [15, 32]. For vocational education, this flexibility is particularly important, as it enables learners to repeatedly practice procedures, review instructional content, and engage in self-directed learning, key factors for achieving skill mastery.

Empirical findings indicate that MAR can enhance learner motivation, spatial ability, and procedural understanding when supported by appropriate instructional design. Cheng and Tsai [36] reported that mobile AR applications promote deeper learner engagement by allowing students to control the pace, sequence, and depth of learning activities. Similarly, Garzón *et al.* [28] found that MAR contributes to improved learning performance in technical subjects by enabling direct interaction with virtual representations of real-world objects. Recent engineering-education studies also highlight that AR-based learning environments can facilitate inquiry-based learning, collaborative problem solving, and interactive exploration of technical systems, which are important elements in modern engineering and vocational training [33]. Nevertheless, despite these promising outcomes, rigorous empirical evidence examining the impact of MAR on objectively measured vocational skills remains limited. Many studies rely primarily on self-reported perceptions or short-term assessments, leaving questions related to long-term skill transfer, procedural accuracy, and workplace applicability largely unanswered.

C. Technology Acceptance Frameworks and UTAUT

Understanding the adoption and sustained use of AR technologies in educational contexts requires a robust theoretical framework. Among existing models, the Unified Theory of Acceptance and Use of Technology (UTAUT), proposed by Venkatesh *et al.* [39], is one of the most comprehensive and empirically validated frameworks. UTAUT synthesizes constructs from eight foundational theories—including the Technology Acceptance Model (TAM), Theory of Planned Behavior (TPB), and the Motivational Model—to explain users' behavioral intention and technology use behavior. The model identifies four core determinants: performance expectancy, effort expectancy, social influence, and facilitating conditions.

A substantial body of empirical research has validated the explanatory power of UTAUT across diverse technological and educational contexts, including e-learning systems, mobile learning platforms, and interactive instructional technologies [40–42]. Recent meta-analytic research on technology acceptance models confirms that UTAUT-based frameworks remain among the most robust approaches for explaining user adoption of emerging digital technologies, including immersive learning systems such as augmented and virtual reality [43]. In educational settings, performance expectancy and effort expectancy consistently emerge as the strongest predictors of behavioral intention, highlighting the central role of perceived usefulness and ease of use in technology adoption.

In the context of the present study, a modified UTAUT framework was adopted by focusing specifically on Performance Expectancy (PE) and Effort Expectancy (EE) as the primary predictors of students' Behavioral Intention (BI) to use AR-based learning media. Prior research in educational technology consistently reports that PE and EE are the most influential determinants of students' intention to adopt digital learning tools, as they directly reflect perceived usefulness and ease of use in learning environments [39, 43, 44].

The constructs of Social Influence (SI) and Facilitating Conditions (FC) were not incorporated into the structural model for two primary reasons. First, previous studies indicate that the influence of SI in student learning contexts is often weaker and highly dependent on social or institutional environments. Second, facilitating conditions such as institutional infrastructure, device availability, and instructional support were relatively controlled in this study by implementing the learning intervention within comparable classroom settings and technological facilities. Therefore, excluding these constructs helped maintain model parsimony while focusing on the constructs most directly related to students' cognitive and usability perceptions of AR learning media.

Nevertheless, the exclusion of SI and FC represents a deliberate model simplification rather than a rejection of the full UTAUT framework. This study, therefore, applies a modified UTAUT model tailored to the educational context of AR-assisted vocational learning. The implications of this modeling decision and its potential limitations are discussed further in the limitations section of the study.

The extension of UTAUT into UTAUT2 further broadens the framework by incorporating additional constructs such as hedonic motivation, price value, and habit. Although UTAUT2 has been applied predominantly in consumer technology research, recent studies indicate its relevance for educational technologies, particularly those characterized by interactive and immersive features [42]. These extensions are particularly relevant in AR-based learning environments, where immersion, interactivity, and experiential engagement may influence learners' motivation to adopt and continuously use the technology.

D. AR and Technology Acceptance in Educational

Although UTAUT has been widely employed to examine technology acceptance in education, research integrating this framework with AR-based learning remains relatively limited. Recent systematic reviews of AR acceptance studies reveal substantial heterogeneity in the theoretical models and variables used, with many studies adopting partial or modified acceptance frameworks rather than a standardized model [45]. Emerging research on immersive learning technologies suggests that AR introduces additional experiential dimensions—such as presence, interactivity, and immersion—that may influence technology acceptance differently compared with traditional information systems [33].

Empirical investigations of AR acceptance in higher education and professional training contexts suggest that UTAUT constructs remain applicable to immersive technologies [46–49]. Performance expectancy and effort expectancy are consistently identified as significant predictors of learners' intention to use AR, while facilitating conditions play an important role in actual usage, particularly in institutional environments with varying levels of infrastructure and technical support [49, 50]. Findings related to social influence are more mixed, with effects varying across cultural contexts, learning environments, and levels of user experience.

E. Integrating Acceptance and AR Effectiveness for Skill Development

A critical gap highlighted in the literature is the limited integration of technology acceptance research with empirical evaluations of learning and skill outcomes. While acceptance studies provide insight into why learners are willing to adopt AR technologies, effectiveness studies often examine learning gains without considering the underlying acceptance mechanisms. This separation restricts understanding of how and under what conditions AR adoption translates into meaningful improvements in vocational competencies.

Recent meta-analytic and systematic research emphasizes the importance of integrating technology acceptance models with performance-based learning evaluation in order to better understand how digital learning technologies influence actual skill outcomes [31, 43]. These integrated perspectives support research approaches that explicitly link technology acceptance mechanisms with objective performance measures, thereby strengthening both theoretical rigor and empirical validity [43].

Within vocational automotive education, such integration is particularly important because the effectiveness of instructional technologies must ultimately be evaluated through improvements in authentic technical performance rather than perceptions alone. Linking acceptance constructs with measurable outcomes-such as procedural accuracy, troubleshooting capability, and task efficiency-provides a stronger explanatory framework for understanding how AR adoption contributes to vocational competence development. This perspective forms the theoretical foundation of the present study, which examines how acceptance of mobile AR technology relates to measurable skill enhancement in learning FWD powertrain systems.

III. Research Hypothesis

Grounded in the reviewed literature on AR-based vocational learning, mobile AR adoption, and technology acceptance theories, this study proposes a set of hypotheses that link key UTAUT constructs with students' behavioral intention and skill enhancement outcomes in FWD powertrain learning.

H1: Performance Expectancy (PE) has a positive effect on Behavioral Intention (BI) to use AR in FWD powertrain learning

Performance expectancy refers to the degree to which individuals believe that a technology will improve their performance. Prior studies in technology acceptance indicate that when learners perceive a technology as useful for improving learning outcomes, their intention to adopt it increases [39, 43, 51]. In the AR-based automotive learning, students who perceive AR as beneficial for understanding mechanical systems are therefore expected to show a stronger intention to use it.

H2: Effort Expectancy (EE) has a positive effect on Behavioral Intention (BI) to use AR in FWD powertrain learning

Effort expectancy reflects the perceived ease of using a technological system. Technology acceptance and cognitive load perspectives suggest that systems that are easier to use reduce cognitive barriers and support learner engagement [39, 52, 53]. When AR applications are perceived as simple and intuitive, students can focus more on learning tasks, which increases their intention to adopt the technology.

H3: Behavioral Intention (BI) has a positive effect on students' Skill Enhancement (SE) in FWD powertrain learning

Behavioral intention is widely recognized as a strong predictor of technology use behavior. In educational environments, a stronger intention to use instructional technologies leads to more interaction, practice, and engagement with the learning system, which supports skill development and competency acquisition [39].

H4: Performance Expectancy (PE) has a positive effect on students' Skill Enhancement (SE) in FWD powertrain learning

From a pedagogical perspective, technologies that provide clear performance benefits can directly support learning outcomes. AR-based visualization and interactive simulations allow learners to explore mechanical relationships and procedural sequences that are difficult to observe through conventional instruction [54]. These capabilities can support deeper understanding and technical skill development in vocational education.

H5: Effort Expectancy (EE) has a positive effect on students' Skill Enhancement (SE) in FWD powertrain learning

Ease of use can also influence learning outcomes because technologies that are simple to operate allow learners to allocate more cognitive resources to understanding instructional content rather than managing system interfaces [53]. This is particularly important in technical training where cognitive resources must focus on mechanical procedures and system operation.

IV. Materials and Methods

A. *Research Design*

This study employed a quasi-experimental quantitative research design combining subjective perception data and objective performance data to comprehensively evaluate the effectiveness of an Augmented Reality (AR) learning tool for Front-Wheel Drive (FWD) powertrain instruction. Unlike a mixed-methods approach, the present study relies exclusively on quantitative data sources. Subjective data were collected through self-administered questionnaires to measure students' technology acceptance and perceived skill enhancement, while objective data were obtained through rubric-based performance assessments to evaluate students' practical competencies in diagnosing and troubleshooting FWD powertrain systems. The research combined cross-sectional survey data (n = 164) with controlled classroom performance data (n = 60) to examine both technology acceptance and measurable skill outcomes.

The study adopted a quasi-experimental classroom comparison design involving an experimental group (AR-based learning) and a control group (conventional instruction). This design enabled direct comparison of learning outcomes while maintaining ecological validity in a real vocational classroom setting.

The overall research framework integrates technology acceptance constructs with measurable learning outcomes, as illustrated in the conceptual model (Fig. 1). This framework posits that Performance Expectancy (PE) and Effort Expectancy (EE) influence students' Behavioral Intention (BI) to use AR, which in turn affects Skill Enhancement (SE). In addition, direct effects of PE and EE on SE were examined to capture both mediated and unmediated relationships.

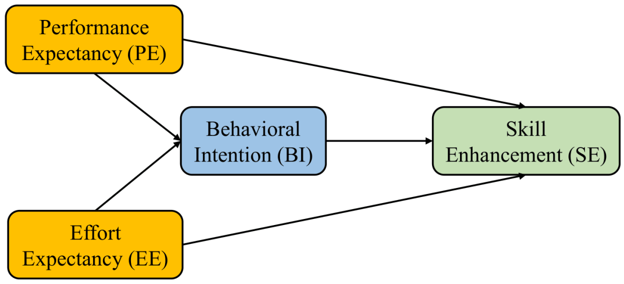


Fig. 1. Conceptual framework.

The AR learning application was developed using the Unity 3D engine (Unity Technologies) for 3D modeling and interaction design, and the Vuforia Engine SDK for marker-based tracking and visualization. The application was deployed on Android smartphones supporting ARCore-compatible cameras with a minimum specification of 4 GB RAM, Snapdragon 660 equivalent processor, and Android 9 or later.

The AR-based learning tool was designed to deliver an interactive and immersive learning experience through widely available mobile devices. The application allows students to interact with animated 3D models of FWD components (e.g., differential, clutch, and transaxle) through rotation, zooming, and exploded-view visualization to observe torque flow and component interactions. To address potential performance issues on lower-specification smartphones, the application was optimized through reduced polygon counts, efficient texture mapping, and adaptive rendering to maintain smooth interaction across a range of devices.

B. *Participants*

The participants consisted of automotive engineering students (vocational diploma and bachelor's programs) enrolled in powertrain-related courses. Two participant groups were involved in the study. The first group included 164 students who completed the questionnaire assessing their perceptions and acceptance of the AR learning tool.

For the objective practical skill assessment, a subgroup of 60 students was selected from two intact classes enrolled in the same powertrain course. One intact class (n = 30) was assigned as the experimental group using the AR-based learning application, while the other class (n = 30) served as the control group receiving conventional instruction based on printed manuals and instructor demonstrations. The assignment, therefore, followed a quasi-experimental procedure using intact classroom groups rather than individual randomization, in order to preserve the natural classroom structure and instructional schedule.

To ensure comparability between groups, baseline equivalence was examined using available demographic characteristics (gender and academic program level). The comparison indicated that the two groups had similar demographic distributions, suggesting comparable starting conditions before the intervention.

The demographic profile of the questionnaire respondents is presented in Table 1.

Table 1. Demographic profile of respondents

Profile	Count	Percent (%)
Female	8	5%
Male	156	95%
Diploma 3	41	25%
Bachelor's Degree	123	75%
Grand Total	**164**	**100.00%**

C. Research Instrument

The primary subjective measurement instrument was a self-administered questionnaire developed based on the Unified Theory of Acceptance and Use of Technology (UTAUT) framework [39]. The questionnaire measured four constructs: Performance Expectancy (PE), Effort Expectancy (EE), Behavioral Intention (BI), and Skill Enhancement (SE). All items were adapted and contextualized for AR-based learning in an FWD powertrain system. Responses were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

Before deployment, the questionnaire items were reviewed by three experts in vocational education and educational technology to ensure content validity and contextual relevance for AR-supported automotive learning. Minor wording adjustments were made based on expert feedback.

Table 2 presents the measurement variables and questionnaire items adapted from Venkatesh *et al.* [39] and contextualized for AR-based learning in FWD powertrain systems.

Table 2. Variables and items (adapted from Venkatesh *et al.* [39])

Item Code	Item
PE1	AR accelerates understanding of FWD operating principles compared to traditional methods.
PE2	AR visualizes the movement of FWD components in real time.
PE3	AR facilitates understanding of abstract concepts such as gear ratios.
PE4	AR helps identify powertrain components more precisely.
PE5	AR enhances understanding of power flow from the engine to the wheels.
PE6	AR deepens understanding of failure modes.
PE7	AR accelerates understanding of FWD operating principles.
PE8	AR visualizes component movement (transaxle) in real time.
EE1	The AR FWD module is easy to learn.
EE2	The AR interface is clear, intuitive, and easy to understand.
EE3	The AR controls and menus are easy to use.
EE4	Skills in using the AR module are quickly acquired.
EE5	The AR instructions and guidance are clear and helpful.
EE6	The AR module can be used without instructor assistance.
EE7	Interaction (rotating, zooming) is not difficult.
EE8	The experience of using AR is stress-free.
BI1	I intend to regularly use the AR module in my learning.
BI2	I will use AR to prepare for exams/assessments.
BI3	I will recommend AR modules to others.
BI4	I prefer AR over traditional learning tools.
BI5	I will look for other AR modules for automotive systems.
BI6	I am willing to spend extra time learning with AR.
BI7	I will use AR in the future.
BI8	I support the integration of AR into vocational curricula.
SE1	More confident explaining FWD powertrain flow
SE2	Skilled in virtual inspection procedures
SE3	Able to predict vehicle behavior when powertrain issues occur
SE4	Able to apply AR knowledge to physical powertrain systems

To obtain objective evidence of skill enhancement, students' practical competencies were evaluated using a performance-based assessment rubric aligned with the vocational skill dimensions reported in the results section. The rubric consisted of five competency aspects reflecting practical performance during automotive powertrain tasks: (1) preparation, (2) work process, (3) work results, (4) professional attitude, and (5) time management.

Preparation assessed students' readiness before performing the diagnostic task, including recognizing FWD powertrain components, preparing the necessary tools, and understanding the initial inspection procedure. Work process evaluated the correctness and sequence of technical procedures performed during diagnostic activities, including the appropriate use of AR visualization and correct inspection steps. Work results measured the accuracy of the final diagnostic outcome, including correct identification of component conditions and successful completion of the assigned task. Professional attitude evaluated observable work behaviors such as discipline, safety compliance, and responsibility during practical activities. Time management assessed the efficiency with which students completed the assigned diagnostic tasks within the allocated time.

Each rubric aspect was scored using a five-point performance scale ranging from 1 to 5 with explicit descriptors: (1) very limited performance—the student is unable to perform the task correctly and requires substantial guidance; (2) basic performance—the student demonstrates partial understanding but performs procedures with significant errors; (3) satisfactory performance—the student completes the task with acceptable accuracy but still requires minor guidance; (4) good performance—the student performs the task correctly with minimal assistance; and (5) excellent performance—the student performs the task accurately, independently, and efficiently according to expected vocational standards.

D. Research Procedure

The research procedure was conducted in four sequential phases: (1) Media Development, (2) Implementation, (3) Data Collection, and (4) Data Analysis, as illustrated in Fig. 2.

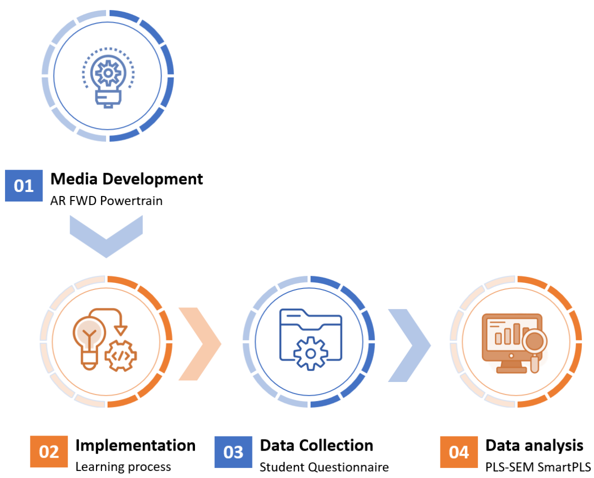


Fig. 2. Research procedure flow.

Table 3 presents the comparison of learning activities between the experimental group (AR-based learning) and the control group (conventional learning) to clarify the experimental design.

Table 3. Comparison of learning activities

Stage	Experimental Group	Control Group
Introduction	Instructor introduces FWD powertrain using AR visualization	Instructor explains FWD system using diagrams and slides
Exploration	Students interact with 3D AR models (rotate, zoom, animation)	Students observe static diagrams and physical components
Practice	Students simulate component inspection and system interaction using AR	Students review printed manuals and observe demonstrations
Problem-solving	Students analyze simulated faults through AR visualization	Students analyze faults based on instructor explanation
Assessment	Practical rubric-based performance evaluation	Practical rubric-based performance evaluation

Phase 1: Media Development. The AR learning tool was developed to support exploration and understanding of FWD powertrain systems. Before classroom implementation, the prototype application underwent a preliminary review to ensure the accuracy of the instructional content and the usability of the AR interaction features. The review focused on the clarity of the visualization, the correctness of the powertrain component representations, and the suitability of the learning interface for vocational learning activities.

Following this preparation stage, a small-scale pilot test was conducted with a limited group of students to evaluate system usability, interaction clarity, and application stability during learning activities. The pilot testing allowed the researchers to observe how students interacted with the AR visualization and identify potential technical or instructional issues during the learning process.

Prototype testing was conducted with a small group of students to evaluate usability, interaction clarity, and system stability before full classroom implementation. Based on observations from the pilot test, minor revisions were applied to improve interface navigation, clarify instructional prompts, and optimize the visualization performance on mobile devices. These adjustments ensured that the AR learning media were functionally stable and suitable for classroom implementation in the subsequent experimental phase.

The application interface included a main menu providing access to AR visualization, instructional materials, job sheets, and interactive component exploration (Fig. 3).

(a)

(b)

Fig. 3. FWD AR application interface. (a) Main menu display (b) Material menu display.

Phase 2: Implementation. The refined AR application was deployed in a teaching factory–based learning environment. During this phase, students interacted with three-dimensional virtual components of the FWD powertrain, such as the differential and clutch mechanisms (Fig. 4). Using smartphones, students manipulated the models through rotation, zooming, and animation controls to observe component interactions and system behavior. Initial guidance was provided to familiarize students with AR navigation and interaction features.

(a)

(b)

Fig. 4. FWD component visualization with AR. (a) differential FWD, (b) clutch and its mechanism.

Phase 3: Data Collection. After completing the AR learning activities, students in the questionnaire group completed the UTAUT-based survey. Concurrently, the subgroup of students participated in rubric-based practical assessments involving diagnosis and troubleshooting tasks.

Phase 4: Data Analysis. Both subjective and objective data were compiled and prepared for statistical analysis, as described in Section IV-F.

E. Skill Measurement and Data Collection

Skill Enhancement (SE) was operationalized using direct performance measures obtained from rubric-based assessments. The assessment criteria included component identification accuracy, procedural correctness, troubleshooting effectiveness, and task completion efficiency. This performance-based evaluation approach is consistent with competency-based assessment practices commonly used in Technical and Vocational Education and Training (TVET) to measure authentic technical skills.

F. Data Analysis

The data were analyzed using SmartPLS 4.0 for the Partial Least Squares Structural Equation Modeling (PLS-SEM) method. The analysis followed a two-stage process involving outer model evaluation and inner model evaluation following recommendations by Hair *et al*. [55] and Henseler *et al*. [56].

For the analysis of rubric-based practical skill scores, descriptive statistical analysis was conducted to summarize students' performance in the experimental group (AR-based learning) and the control group (conventional instruction). The analysis focused on comparing the mean rubric scores obtained from the practical performance assessment. Because the results section reports the practical performance outcomes in terms of rubric scores, the analysis emphasized descriptive comparison of the average scores between the two instructional conditions.

Descriptive statistics, including mean values and standard deviations of the rubric scores, were calculated to provide an overview of students' practical skill performance in each group. These statistics enabled a direct comparison of practical competency outcomes between students who learned using the AR-based instructional media and those who received conventional instruction. This approach ensured consistency between the data analysis procedure and the results presented in the study, which focuses on the observed practical performance scores.

Consequently, the statistical analysis of practical skill performance did not include inferential indicators such as normality tests, homogeneity tests, *p*-values, or effect size measures, since these statistics are not reported in the results section. The analysis, therefore, emphasizes descriptive interpretation of the rubric-based practical scores to illustrate the differences in observed student performance between the two learning approaches.

G. Ethical Approval

This study received ethical approval from the Ethics Committee of Universitas Negeri Padang (No. 00011/EE/2025/0040211371). Participation was voluntary, informed consent was obtained from all participants, and all data were collected and analyzed anonymously to ensure confidentiality and ethical compliance.

V. Results

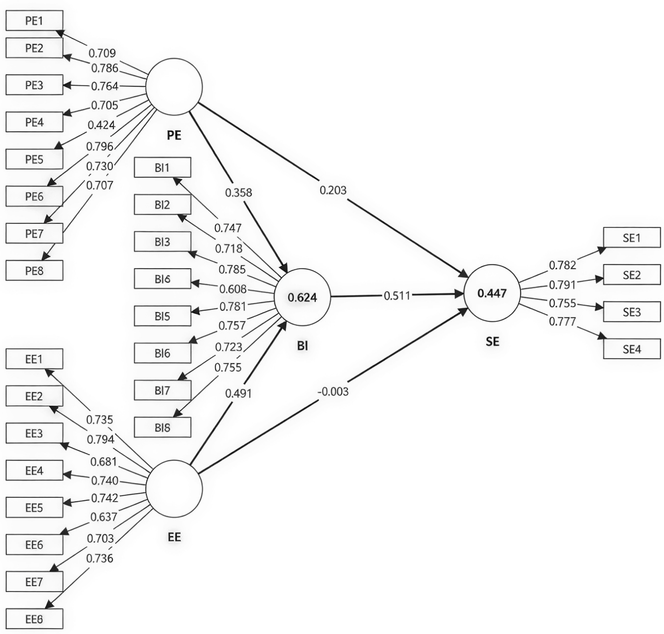
A. Descriptive Statistics

Descriptive statistics were first examined to provide an overview of students' responses to the Augmented Reality (AR)-based Front-Wheel Drive (FWD) powertrain learning module. As presented in Table 4, all constructs demonstrated generally high mean values (approximately 3.8–4.3 on a five-point Likert scale), indicating that students perceived the AR learning environment as useful, accessible, and supportive for skill development. Rather than isolated responses, this pattern suggests a consistently positive learning perception Performance Expectancy (PE), Effort Expectancy (EE), Behavioral Intention (BI), and Skill Enhancement (SE) indicators.

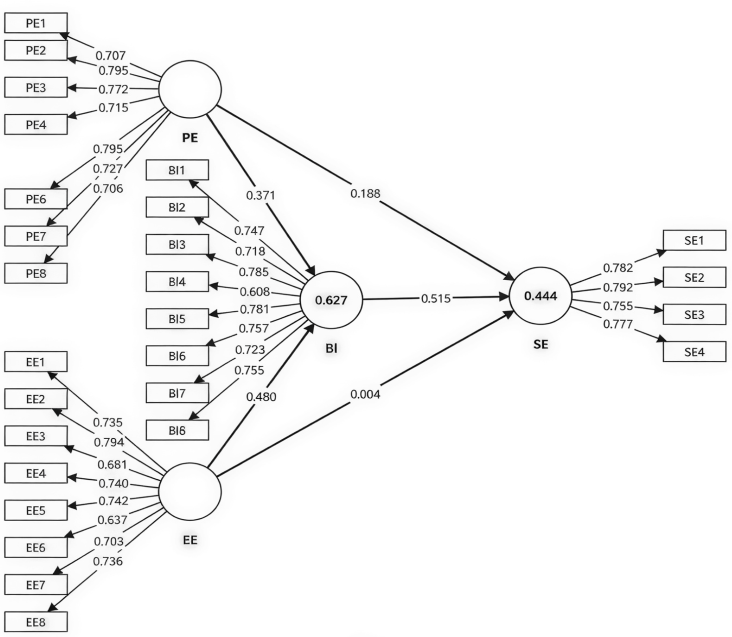
Assessment of data distribution showed that skewness and excess kurtosis values for all items were within the acceptable threshold of ±2, indicating no substantial deviation from normality. Although Partial Least Squares Structural Equation Modeling (PLS-SEM) does not require strict normality assumptions, these results strengthen the robustness of subsequent multivariate analysis.

Table 4. Descriptive statistics and normality assessment

Item Code	Min	Max	Mean	Standard deviation	Excess kurtosis	Skewness
PE1	1	5	4.049	0.779	–0.047	–0.398
PE2	2	5	4.274	0.693	–0.363	–0.54
PE3	3	5	4.299	0.682	–0.815	–0.461
PE4	1	5	4.329	0.733	1.326	–0.983
PE5	2	5	3.878	0.651	–0.026	–0.139
PE6	2	5	4.244	0.691	–0.39	–0.479
PE7	2	5	4.11	0.826	–0.53	–0.535
PE8	2	5	4.159	0.796	–0.876	–0.44
EE1	2	5	3.97	0.815	–0.857	–0.217
EE2	2	5	4.207	0.736	–0.371	–0.536
EE3	2	5	4.213	0.705	–0.523	–0.435
EE4	2	5	4.134	0.808	0.138	–0.741
EE5	3	5	4.299	0.664	–0.759	–0.425
EE6	1	5	3.945	0.964	–0.268	–0.589
EE7	2	5	4.305	0.693	–0.315	–0.604
EE8	1	5	4.299	0.79	1.079	–1.037
BI1	2	5	3.933	0.774	–0.781	–0.122
BI2	2	5	3.994	0.745	–0.471	–0.258
BI3	2	5	4.177	0.773	–0.98	–0.398
BI4	1	5	4.122	0.722	0.864	–0.581
BI5	2	5	4.146	0.674	–0.335	–0.306
BI6	2	5	4.024	0.671	–0.379	–0.151
BI7	3	5	4.213	0.688	–0.88	–0.307
BI8	2	5	4.189	0.77	–0.357	–0.583
SE1	2	5	3.799	0.79	–0.385	–0.223
SE2	2	5	3.793	0.8	–0.477	–0.183
SE3	2	5	3.896	0.793	–0.641	–0.181
SE4	2	5	4.073	0.762	–1.013	–0.208



(a)



(b)

Fig. 5. PLS-path model (a) Initial PLS-path model; (b) Modified PLS-path model.

Before to structural model testing, an initial path model grounded in the Unified Theory of Acceptance and Use of Technology (UTAUT) framework was specified (Fig. 5(a)). Following empirical testing of the measurement model, several indicators with low outer loadings were removed to improve construct reliability and validity. This refinement step resulted in a more stable empirical model that better represents the observed relationships among constructs (Fig. 5(b)).

B. Measurement Model Evaluation

The measurement model was evaluated to assess construct reliability and validity. Indicator reliability was confirmed as most outer loadings exceeded the recommended threshold of 0.70. A small number of indicators (PE4, BI4, and EE6) exhibited loadings between 0.60 and 0.70; however, these items were retained due to their theoretical relevance and acceptable contribution to composite reliability, in accordance with methodological guidelines [46].

Convergent validity was established for all constructs, as reflected by Average Variance Extracted (AVE) values greater than 0.50. Internal consistency reliability was also satisfactory, with Cronbach's alpha, rho_A, and Composite Reliability (CR) values exceeding 0.70 for all constructs (Table 5). These results confirm that the measurement instruments reliably capture the latent constructs associated with AR acceptance and vocational skill enhancement.

Discriminant validity was assessed using the Heterotrait–Monotrait (HTMT) ratio. As shown in Table 6, all HTMT values were below the conservative threshold of 0.90, confirming that the latent constructs were empirically distinct and that multicollinearity between constructs did not pose a concern.

C. Structural Model Evaluation and Hypothesis Testing

The structural model was evaluated to test the hypothesized relationships among Performance Expectancy (PE), Effort Expectancy (EE), Behavioral Intention (BI), and Skill Enhancement (SE). Fig. 6 illustrates the standardized path coefficients, while detailed statistical results are summarized in Table 7.

The results show that Performance Expectancy and Effort Expectancy are both significant predictors of Behavioral Intention to use AR in FWD powertrain learning. Together, these variables explain a substantial proportion of students' intention to adopt the AR system ($R^2 = 0.623$), indicating that perceived usefulness and ease of use play a dominant role in AR acceptance within vocational learning.

Table 5. Measurement model validity and reliability

Item Code	Outer loadings	AVE	Cronbach's alpha	Rho_a	Rho_c
BI1	0.747	0.542	0.878	0.881	0.904
BI2	0.718				
BI3	0.785				
BI4	0.608				
BI5	0.781				
BI6	0.757				
BI7	0.723				
BI8	0.755				
EE1	0.735	0.522	0.868	0.873	0.897
EE2	0.794				
EE3	0.681				
EE4	0.74				
EE5	0.742				
EE6	0.637				
EE7	0.703				
EE8	0.736				
PE1	0.707	0.557	0.867	0.869	0.898
PE2	0.795				
PE3	0.772				
PE4	0.715				
PE6	0.795				
PE7	0.727				
PE8	0.706				
SE1	0.782	0.603	0.781	0.782	0.859
SE2	0.792				
SE3	0.755				
SE4	0.777				

Table 6. HTMT discriminant validity results

	BI	EE	PE	SE
BI				
EE	0.858			
PE	0.82	0.837		
SE	0.784	0.637	0.676	

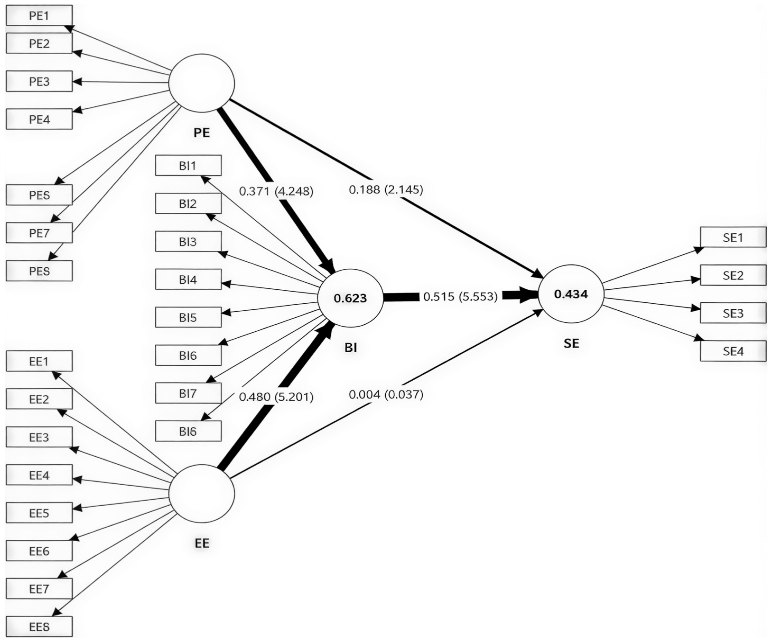


Fig. 6. PLS-path model hypotheses.

Table 7. Summary of hypotheses testing results

H	Path	Std. Beta	Std. Error	T-value	P values	Bias	Confidence internal		D
							5.00%	95.00%	
H1	PE → BI	0.371	0.087	4.248	0	0.008	0.226	0.515	S
H2	EE→ BI	0.48	0.092	5.201	0	–0.005	0.319	0.622	S
H3	BI → SE	0.515	0.093	5.553	0	0.005	0.358	0.662	S
H4	PE → SE	0.188	0.088	2.145	0.016	–0.004	0.035	0.324	S
H5	EE → SE	0.004	0.099	0.037	0.485	0.004	–0.165	0.162	NS

Note: H = Hypotheses, D = Decision, S = Supported, NS = Not Supported

Behavioral Intention emerged as the strongest predictor of Skill Enhancement, demonstrating that students who are more willing to engage with AR technologies tend to achieve better practical learning outcomes. This finding highlights the mediating role of technology acceptance in translating digital learning tools into measurable vocational skill gains.

Performance Expectancy also contributed directly to Skill Enhancement, suggesting that students who perceive AR as beneficial for learning are more likely to demonstrate improved technical performance. In contrast, Effort Expectancy did not show a significant direct relationship with Skill Enhancement. This indicates that ease of use alone does not automatically translate into improved skills, but instead influences skill development indirectly through Behavioral Intention.

Importantly, the coefficient of determination for Skill Enhancement reached $R^2 = 0.434$, meaning that 43.4% of the variance in students' vocational skill outcomes is explained by the combined effects of BI, PE, and EE. In a vocational education context, this level of explanatory power can be interpreted as moderate-to-strong predictive capability, demonstrating that AR adoption factors meaningfully contribute to skill development.

Overall, hypotheses H1, H2, H3, and H4 were supported, while H5 (EE → SE) was not supported. Despite the non-significant direct effect, the significant EE → BI and BI → SE relationships indicate an indirect pathway through which perceived ease of use contributes to skill enhancement.

D. Objective Skill Enhancement Results

Objective skill enhancement was evaluated using rubric-based performance assessments comparing an experimental group that used the AR learning tool and a control group that received traditional instruction. As presented in Table 8, students who used the AR-based learning system achieved a noticeably higher overall performance level than those in the conventional learning group.

Table 8. Comparison of skill enhancement between experimental and control groups

Aspects	Experimental Class		Control Class	
	Skill enhancement	Decision	Skill enhancement	Decision
Preparation	90.83%	HS	81.67%	S
Work Process	86.25%	HS	76.81%	S
Work Results	85.00%	S	73.96%	S
Attitude	88.06%	HS	75.56%	S
Time	86.11%	HS	77.22%	S
Average	**87.25%**	**HS**	**77.04%**	**S**

Note: HS = Highly Skilled, S = Skilled.

The experimental group obtained an average skill score of 87.25% (Highly Skilled), while the control group achieved 77.04% (Skilled). This gap indicates that the integration of AR technology provides measurable advantages for developing practical competencies in FWD powertrain learning tasks.

Across the evaluated dimensions-preparation, work process, work results, attitude, and time management-the experimental group consistently demonstrated stronger outcomes. The largest improvements were observed in preparation, work process, and professional attitude, suggesting that AR supports not only technical understanding but also procedural readiness and work discipline during practical activities. Although both groups were categorized as *Skilled* in terms of work results, the experimental group still showed a higher achievement level, indicating more accurate task execution and improved technical outcomes.

Overall, these results provide objective empirical evidence that AR-supported learning environments enhance vocational skill acquisition beyond students' self-reported perceptions, reinforcing the value of immersive visualization technologies in technical education.

VI. Discussion

A. Discussion of Key Findings

This study provides empirical evidence that the integration of Augmented Reality (AR) into vocational automotive education can significantly enhance students' technical skills in Front-Wheel Drive (FWD) powertrain learning. Students who engaged with the AR-based instructional module consistently outperformed their peers in the control group across multiple dimensions of practical performance, including task preparation, procedural execution, time management, and overall task completion. These results indicate that AR-supported learning facilitated more structured, efficient, and accurate engagement with complex mechanical tasks. These findings suggest that immersive visualization and interactive manipulation of mechanical components can reduce cognitive abstraction in technical learning, enabling students to better connect conceptual knowledge with hands-on procedural tasks [31, 54, 57]. The findings are consistent with and extend prior research demonstrating that immersive and interactive learning environments support deeper understanding and improved performance in vocational and engineering education [58–61].

A key contribution of this study lies in its emphasis on objective, rubric-based assessment of vocational skills. Unlike many previous AR studies that rely predominantly on self-reported perceptions, attitudes, or behavioral intentions, this research evaluated students' competencies using standardized performance criteria aligned with authentic vocational tasks. The ability to directly assess component identification, fault diagnosis, and procedural application provides robust empirical support for the claim that AR-based learning can translate into measurable technical skill improvement. By combining technology acceptance modeling with objective skill assessment, this study demonstrates how instructional technology adoption can move beyond attitudinal outcomes toward demonstrable competency development in engineering-related training contexts [62, 63].

Consistent with the proposed hypotheses, Performance Expectancy and Effort Expectancy positively influenced Behavioral Intention (H1–H2 supported), Behavioral Intention strongly predicted Skill Enhancement (H3 supported), and Performance Expectancy had a direct positive effect on Skill Enhancement (H4 supported). However, Effort Expectancy did not have a significant direct effect on Skill Enhancement (H5 not supported), indicating that perceived ease of use contributes to skill gains primarily by increasing learners' intention to use AR.

This unexpected finding suggests that ease of use alone is insufficient to produce measurable improvements in vocational performance. Instead, Effort Expectancy appears to function as an enabling condition that encourages learners to adopt and repeatedly engage with the technology. Once students are motivated to use AR (Behavioral Intention), the learning benefits emerge through sustained interaction with the instructional environment. This mediating mechanism aligns with pedagogical perspectives that emphasize learner engagement and active interaction as key drivers of skill acquisition in technical training environments [41, 51, 64].

The results of the structural model analysis further validate the applicability of the Unified Theory of Acceptance and Use of Technology (UTAUT) in explaining AR adoption within vocational learning environments. Performance Expectancy (PE) and Effort Expectancy (EE) were both found to exert significant positive effects on Behavioral Intention (BI), indicating that students were more inclined to adopt AR when they perceived it as beneficial for learning and manageable within instructional activities. Similar patterns have been reported in recent engineering education studies where perceived usefulness and usability were identified as key determinants of AR adoption in laboratory training and industrial simulation environments [24, 65].

Importantly, Behavioral Intention emerged as a strong and significant predictor of Skill Enhancement, highlighting its mediating role between technology acceptance and actual learning outcomes. This result demonstrates that acceptance constructs are not merely attitudinal but can translate into tangible performance gains when learners actively engage with instructional technologies. While Performance Expectancy also had a direct positive effect on skill enhancement, the absence of a significant direct effect of Effort Expectancy on skills suggests that ease of use alone does not automatically lead to improved vocational performance. Instead, its influence operates indirectly through learners' motivation and intention to use the technology. Comparable findings have been reported in recent AR-supported engineering and medical training research where usability primarily affects engagement and adoption rather than direct skill outcomes [24, 62].

These findings are consistent with recent studies highlighting that technological infrastructure and device variability remain important moderating factors in AR-based educational interventions [66]. As a result, institutions considering AR adoption should establish minimum device specifications, ensure application optimization, and provide technical support to promote equitable access and consistent learning outcomes.

Teacher readiness emerged as another critical factor in the successful integration of AR into vocational instruction. Consistent with previous research [55], this study suggests that educators' pedagogical and technological competencies significantly influence the extent to which AR can be effectively embedded into learning activities. Without adequate professional development and instructional guidance, the pedagogical potential of AR may remain underutilized. Furthermore, the experiential and affective dimensions of AR use, such as interface design, usability, and emotional engagement, play an important role in sustaining learner motivation and engagement. Recent studies in engineering and STEM education emphasize that AR systems designed with strong user experience principles tend to produce higher engagement and more effective procedural learning outcomes [24, 65].

The present findings are further supported by earlier studies emphasizing the value of interactive, task-oriented, and contextually rich AR learning environments. Research by Kuanbayeva *et al*. [57] and Saputro *et al.* [63] demonstrated that AR can effectively bridge the gap between theoretical knowledge and practical application by promoting active participation and contextualized skill mastery. In comparison with AR applications in other engineering domains, such as mechanical assembly training and industrial maintenance simulation, the present results indicate that automotive powertrain education similarly benefits from spatial visualization and interactive system exploration [31, 62].

From an engineering education perspective, this study addresses a critical gap in vocational learning research by empirically linking technology acceptance factors with objectively measured technical skill performance in automotive training. Unlike prior studies that primarily focused on learners' perceptions or intentions, this research demonstrates that AR not only influences behavioral intention through performance and effort expectancy but also results in measurable improvements in procedural accuracy, workflow efficiency, and system-level understanding of FWD powertrain systems. This integration of acceptance modeling and performance-based evaluation contributes to a growing body of evidence that AR can serve as an effective instructional technology for competency-oriented engineering education [24, 31, 54].

B. Limitations and Future Research

Despite its contributions, this study has several limitations that should be acknowledged. First, the AR intervention was conducted over a relatively short instructional period, which limits the ability to examine long-term skill retention and the transfer of learning to authentic workplace environments. Second, the study focused specifically on Front-Wheel Drive (FWD) powertrain learning within a single institutional context, which may limit the generalizability of the findings to other automotive subsystems, educational levels, or geographic regions. Third, the implementation relied on smartphone-based AR platforms, which, while accessible, may not fully capture the pedagogical potential of more advanced AR systems such as head-mounted displays or mixed reality environments.

Future research should therefore investigate the longitudinal effects of AR-based learning on vocational skill retention, professional readiness, and workplace performance. Multi-institutional studies with larger and more diverse samples are also recommended to enhance external validity. Further studies are also encouraged to examine AR-based learning in more complex automotive systems, such as Electric Vehicle (EV) powertrains, hybrid propulsion systems, and Electronic Control Unit (ECU) diagnostics, where spatial visualization and system interaction may present even greater instructional benefits. Additionally, future work may explore the integration of structured teacher professional development programs, higher-end AR hardware, and extended acceptance frameworks such as UTAUT2 to provide a more comprehensive understanding of how technological, pedagogical, and contextual factors jointly influence learning outcomes in vocational and engineering education.

VII. Conclusion

This study confirms that Augmented Reality (AR) can effectively enhance students' technical competencies in learning Front-Wheel Drive (FWD) powertrain systems. The results show that Performance Expectancy (PE) and Effort Expectancy (EE) positively influence Behavioral Intention (BI), which in turn supports improved procedural accuracy, workflow efficiency, and task performance in automotive practice. Students who used AR demonstrated stronger technical skill outcomes compared with those who learned through conventional instruction.

The main contribution of this research is the integration of a technology acceptance perspective with objective, rubric-based assessment of vocational technical skills. By linking user acceptance constructs with observable skill performance, this study provides empirical evidence that AR-supported learning can strengthen competency development in automotive engineering education.

From a practical standpoint, the findings suggest that curriculum developers should consider integrating mobile AR modules into powertrain learning, particularly for topics requiring spatial visualization and mechanical system interaction. AR can support safer and more efficient preparation before students engage with real workshop equipment. Future research should explore long-term skill retention, broader institutional implementation, and the development of scalable AR learning ecosystems for emerging automotive technologies.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, M. and D.F.; Methodology, M., N.H., V.T., and D.T.P.Y.; Validation, D.F. and H.-C.K.; Formal analysis, N.H. and M.S.H.R.; Investigation, D.T.P.Y. and H.-C.K.; Data curation, M.S.H.R., V.T., and N.H.; Writing—original draft preparation, M. and R.P.; Writing—review and critical editing, D.F., D.T.P.Y., and H.-C.K.; Visualization, M.S.H.R.; Supervision, H.-C.K. All authors made substantial contributions to the work, critically revised the manuscript, approved the final version, and agreed to be accountable for the accuracy and integrity of the research.

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