Augmented Reality in Automotive Technical Training: Technological Innovation Through Mobile Applications in Trujillo

An Immersive Technologies-Based Approach to Automotive Maintenance Training

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Abstract—**This study evaluated the impact of an Augmented Reality (AR)-based mobile application on technical training in automotive maintenance at a company in Trujillo, Peru. The application was developed using Unity 3D, the Vuforia marker-based recognition engine, and C#, enabling technicians to interact with three-dimensional models of automotive components — including engines, valve trains, crankshafts, and braking systems — through touch-based rotation, zoom, and perspective controls overlaid on physical QR markers. This marker-based interaction architecture distinguishes the system by enabling step-by-step guided visualization of complex maintenance procedures without requiring physical equipment access. A posttest-only control group experimental design was employed with 60 technicians randomly assigned to experimental and control groups, using the Mobile-D methodology for software development. The results revealed a significant improvement in technical content comprehension, a 46.6% reduction in average training time (from 10,862 to 5,784 seconds), and increased satisfaction levels, reaching a mean score of 4.0 versus 2.6 in the control group. The Mann–Whitney U test confirmed statistically significant differences ($p = 0.001$) across all indicators, with large effect sizes (Rosenthal's $r \geq 0.86$). These findings suggest that AR-based mobile applications represent a viable instructional approach for automotive maintenance training, though broader generalization requires validation across diverse organizational contexts.**

Keywords—Augmented reality; marker-based AR; automotive maintenance training; mobile application; technical comprehension; training efficiency; experimental design

I. INTRODUCTION

Digital transformation has profoundly reshaped training processes in technical education, particularly in fields that require the mastery of specialized practical skills, such as the automotive sector. Augmented Reality (AR) has emerged as an innovative technology with the potential to support the development of technical competencies by enabling the overlay of virtual content onto real-world environments through mobile devices. This approach enables technicians to explore simulations of complex systems and technical procedures without the need to manipulate actual physical equipment [1].

In the field of technical automotive education, the use of emerging technologies has become increasingly relevant due to the industry's dynamic nature and high technological demands. Advances in vehicle systems, electronic control, predictive maintenance, and automated process management have led educational institutions to rethink their teaching methodologies [2]. However, previous evidence in this area should be interpreted with caution. Although VR/AR-based educational environments have been proposed to support automotive and manufacturing training, some implementations have been developed mainly in university laboratory settings and evaluated through student experience or satisfaction measures rather than through controlled experimental comparisons in real workplace training contexts [3]. Therefore, while AR offers interactive virtual environments with potential to support safer and more accessible learning, further empirical evidence is still needed to evaluate its impact on measurable training outcomes such as technical comprehension, task completion time, and participant satisfaction in authentic automotive maintenance environments.

The contributions of Augmented Reality (AR) are not limited to the three-dimensional visualization of mechanical components, but also include step-by-step guided training through visual cues, animations, highlighted objects, and real-time instructional feedback. These features may support technician autonomy and reduce procedural errors, particularly in maintenance tasks that require spatial orientation and sequential execution. However, previous evidence suggests that AR effectiveness is task-dependent. For instance, one study found that traditional training performed better for single-level maintenance tasks, whereas AR showed greater advantages in complex multi-level tasks, although the generalizability of its findings was limited by specific hardware conditions, such as the restricted field of view of HoloLens 2, as well as by the need for further comparative and longitudinal evaluations [4]. Therefore, AR shows potential for practical maintenance training, but its effectiveness may vary according to task complexity and implementation conditions.

Several studies have reported that Augmented Reality (AR) can support industrial maintenance activities by providing contextual information, visual guidance, and interactive assistance during diagnostics, inspections, assembly, and maintenance procedures [5]. However, despite the promising results of AR applications in maintenance, their industrial adoption is still limited by technical constraints, fragmentation among hardware and software solutions, tracking accuracy issues, and the lack of maturity of some AR systems for real operational environments. Similarly, research on predictive maintenance and intelligent sensors in smart factories highlights that efficiency improvements depend not only on visualization technologies, but also on the availability of reliable data, sensor interoperability, cybersecurity, and the effective integration of Industry 4.0 technologies [6].

At a global level, recent studies indicate that Augmented Reality (AR) is increasingly aligned with the principles of Industry 4.0, particularly in smart engineering manufacturing environments where technologies such as the Internet of Things (IoT), intelligent sensors, data analytics, and predictive maintenance are progressively integrated [7]. However, this alignment is often discussed from a technological or manufacturing perspective rather than from a pedagogical standpoint. Therefore, in automotive maintenance training, the value of AR should not be assumed only from its compatibility with Industry 4.0, but also from how its content, interaction design, and simulated procedures support the actual training needs of technicians.

In local contexts such as the city of Trujillo, where technical education programs seek to adapt to the challenges of a changing industrial environment, the incorporation of Augmented Reality (AR) may represent a strategic opportunity to strengthen the training of automotive technicians. The integration of mobile applications with AR content can provide more accessible training resources and reduce exclusive dependence on physical equipment; however, accessibility does not necessarily ensure effective learning, since outcomes also depend on instructional design, device availability, user familiarity with mobile technologies, and the realism of simulated procedures. Empirical evidence evaluating these benefits in local technical training settings remains scarce, underscoring the need for context-specific studies. Therefore, evaluating mobile AR in an automotive maintenance environment in Trujillo is necessary to determine whether these potential benefits translate into improvements in technicians' comprehension, training time, and satisfaction [8].

Technical training in the automotive field represents a fundamental pillar to ensure quality, efficiency, and safety in vehicle maintenance services. However, in contexts where traditional teaching methods still predominate—based on static theoretical lectures and limited instructional materials—training processes face significant barriers, resulting in a gap between the knowledge acquired in the classroom and the practical competencies required in the workplace, which affects the professional performance of future technicians. Additionally, the lack of innovative pedagogical strategies and the limited use of educational technologies hinder the development of technical, analytical, and problem-solving skills, which are essential to address the continuous technological advances in the automotive sector [9].

Difficulties in understanding complex mechanical procedures, excessive session duration, and low participant motivation reflect a mismatch between industry demands and the competencies acquired in the classroom. This situation becomes even more critical in the context of the rapid technological advancement of the automotive industry, where new vehicle models integrate electronic and digital systems that require more specialized technical skills [10].

One of the alternatives with the greatest potential has been the development of mobile applications based on Augmented Reality (AR), a technology that enables the visualization and interaction with three-dimensional models of automotive components through mobile devices [11]. This approach allows the simulation of real procedures without requiring direct access to physical equipment, which may reduce operational risks and facilitate autonomous training. However, its contribution to knowledge retention and practical skill transfer should be interpreted cautiously when long-term follow-up assessments are not included. Therefore, the incorporation of this tool into teaching processes represents an opportunity to improve technical training, provided that its effects are evaluated through objective and context-specific indicators.

Collectively, the reviewed literature reveals three recurring methodological gaps that limit the applicability of prior findings to real-world automotive maintenance training. First, most AR evaluations have been conducted in university laboratory settings using satisfaction or perceived usability measures, rather than through controlled experimental designs with objectively measured learning outcomes in authentic workplace environments. Second, robustness assessments have been largely restricted to specific hardware configurations — such as head-mounted displays with limited fields of view — without testing marker-based mobile AR systems under the operational conditions of actual maintenance workshops. Third, longitudinal and comparative evidence on training efficiency indicators, such as task completion time and effect size reporting, remains scarce. The present study directly addresses these gaps by implementing a marker-based AR mobile application in a real automotive company, employing a true experimental posttest-only design with random group assignment, and evaluating outcomes through three objective indicators with effect size analysis.

Research Hypotheses. The general hypothesis of this study states that the implementation of a mobile application based on Augmented Reality (AR) improves the training process of automotive maintenance technicians. Furthermore, the following specific hypotheses were formulated: (H1) the AR-based mobile application improves the understanding of technical training content; (H2) the AR-based mobile application reduces the average duration of training sessions; and (H3) the AR-based mobile application increases participant satisfaction with the training method used. These hypotheses were examined through the development and evaluation of an interactive learning tool that allows users to explore diagnostic, repair, and inspection processes in a visual and immersive manner.

II. THEORETICAL FRAMEWORK

A. Augmented Reality

Augmented Reality (AR) is a technology that enables the superimposition of digital information—such as three-dimensional models or instructional content—onto the real-world environment through the use of mobile devices or smart displays. In the field of technical education, AR has been incorporated as an innovative tool to simulate complex procedures, visualize internal machine components, and develop practical skills without directly intervening with physical equipment [12]. This technology enhances the understanding of technical processes, increases technician interaction, and allows for the autonomous repetition of training tasks, resulting in a more dynamic and meaningful learning experience [13].

B. Maintenance in Automotive Systems

Predictive maintenance is based on the continuous monitoring of equipment to identify abnormal conditions that may lead to functional failures. In the automotive sector, this strategy has become a key approach for reducing operational costs, extending component lifespan, and improving vehicle safety. Through the use of smart sensors and machine learning algorithms, it is possible to detect unusual behavioral patterns in engine systems, thereby anticipating potential failures before they occur. When this information is integrated with Augmented Reality (AR) visualizations, technicians can interpret data more quickly and accurately, facilitating decision-making during the maintenance process [13].

C. Mobile Applications

Mobile applications have revolutionized access to knowledge by providing versatile platforms for digital education. In the context of automotive technical training, they enable technicians to interact with simulators, visual manuals, and immersive environments from virtually any location, thereby optimizing autonomous practice. The integration of these applications with Augmented Reality (AR) enables the virtual representation of engines, transmissions, and other vehicle components, promoting both visual and experiential learning. Furthermore, the continuous updates supported by these platforms ensure that training content remains aligned with technological advancements in the sector, thereby fostering more relevant and up-to-date technical training [14].

III. MATERIALS AND METHODS

A. Type of Research

This study is classified as applied research, as it focuses on analyzing and solving specific problems affecting a particular context. The primary objective was to generate practically useful knowledge aimed at improving processes, optimizing resources, and transforming situations identified as problematic. This approach enabled the integration of theoretical foundations with practical application, directing the results toward the implementation of context-specific solutions. Furthermore, the study aimed to provide scientific evidence to support informed decision-making, the design of improvement strategies, and the innovation of the evaluated procedures, thereby enhancing the relevance and applicability of the findings obtained [15].

B. Research Design

The study employed a true experimental design — specifically, a posttest-only control group design — characterized by the intentional manipulation of an independent variable to observe its effect on a dependent variable under controlled conditions. This design allowed the establishment of cause-and-effect relationships with a higher level of certainty, as it included the random assignment of participants into two groups: an experimental group that received the intervention and a control group that did not receive any treatment. Given that participants were randomly assigned to groups, pre-test measurements were not required, as randomization ensures initial equivalence between the control and experimental groups, thereby controlling for pre-existing differences without the need for baseline measurements. The randomization process helped minimize the influence of extraneous variables and potential biases, thereby ensuring the internal validity of the study. Furthermore, the rigorous control of experimental conditions enabled the comparison of outcomes between both groups, facilitating the identification of effects exclusively attributable to the applied intervention [16].

C. Variables and Operationalization

1) Independent variable: Augmented Reality (AR)

2) Conceptual definition: Augmented Reality (AR) refers to a technology that enables the superimposition of virtual elements onto real-world environments, facilitating the visualization and interaction with three-dimensional content through mobile devices. In educational contexts, it has been established as a tool that enhances comprehension, increases technicians' motivation, and enables the simulation of practical experiences that are difficult to replicate in conventional settings [17].

3) Operational definition: This variable was assessed through the "Implementation of the Mobile Application," assigning the value "NO" prior to the intervention and "YES" after its implementation, using a nominal measurement scale.

4) Dependent variable: Technical Training Performance.

5) Conceptual definition: Technical training performance refers to the level of achievement attained by participants during the training process, determined through the completion of practical activities, evaluation tests, and observed performance outcomes [18].

6) Operational definition: It was measured using three key indicators:

a) Level of understanding of technical procedures,

b) Average time required to complete simulated activities, and

c) Degree of perceived satisfaction with the training process. Data were collected through evaluation records and structured surveys, using ordinal and ratio scales according to the nature of each indicator.

D. Population, Sample, and Sampling

The population is defined as the set of individuals, objects, or events that share common characteristics relevant to the purposes of a research study. It represents the entire group from which information is intended to be obtained and is essential in the study design to determine the scope and representativeness of the results. The characteristics that define a population may include variables such as age, educational level, geographic location, profession, among others. Depending on the methodological approach, research may involve large or specific populations according to the objectives of the study [19].

The population consisted of automotive maintenance technicians working at a company in Trujillo, Peru. The sample comprised a total of 60 technicians selected through purposive sampling, based on criteria such as homogeneity in training level and availability to participate in the proposed activities. Once the sample was defined, participants were randomly assigned to one of two groups of 30 individuals each: an experimental group, which received the AR-based intervention, and a control group, which completed training without the technological tool. This combination of purposive sampling for participant selection and random assignment for group allocation is consistent with true experimental designs in applied research.

E. Data Collection Techniques and Instruments

The research team collected data using quantitative techniques through previously validated instruments. Three main instruments were applied: an evaluation questionnaire to measure content comprehension, a record sheet to calculate the average training time, and a satisfaction survey administered at the end of the process. The collected data were organized and systematized for analysis using descriptive and inferential statistics. Subsequently, Jamovi software was employed to calculate statistical measures such as the mean, standard deviation, and value range. For group comparisons, normality tests were performed, and the Mann–Whitney U test was used due to the non-normal distribution of the collected data. Additionally, effect size was calculated using Rosenthal's r coefficient ($r = Z / \sqrt{N}$) to assess the practical significance of observed differences between groups.

F. Procedures

The study followed several phases based on the Mobile-D methodology, which is considered appropriate for mobile software development projects due to its agile and user-centered approach. In the initial phase, the Augmented Reality (AR)-based mobile application was designed using tools such as Unity 3D, Android Studio, and the Vuforia engine, which enabled the creation of interactive environments and the integration of three-dimensional models. Subsequently, the application was implemented by incorporating functionalities focused on the visualization and manipulation of virtual automotive components. The application was then installed on the technicians' mobile devices, ensuring compatibility with operating systems and proper execution of the programmed functions. Finally, functional and usability testing were conducted to verify application performance and ensure its correct operation within the implementation context.

During the training phase, participants accessed interactive thematic modules that included the visualization of automotive components in 3D. Repetition of activities was permitted as needed, promoting personalized learning. Upon completion of the training process, the corresponding evaluation instruments were administered to measure comprehension levels, time spent, and satisfaction with the training process. Finally, the collected data were processed and analyzed to determine the impact of the technological tool on the training of automotive maintenance technicians.

IV. SOFTWARE DEVELOPMENT FRAMEWORK

To develop the Augmented Reality (AR)-based mobile application for training automotive maintenance technicians, the team adopted the Mobile-D methodology, an agile approach specifically designed for mobile software projects. This methodology consists of six progressive phases: Exploration, Initialization, Production, Stabilization, System Testing, and Deployment. Each phase addressed a specific set of activities that facilitated the efficient organization of the development process and ensured the adaptation of the product to the needs of end users.

A. Exploration Phase

The Exploration phase marked the starting point for the development of the Augmented Reality (AR)-based mobile application. During this stage, the team analyzed the educational and technological context in which the solution would operate to understand users' needs and their operational environment. The researchers conducted a preliminary needs assessment to identify the limitations of the traditional training model, as well as opportunities for improvement through technological tools. Based on this analysis, the team established the initial system objectives and proposed a mobile-based solution integrating Augmented Reality elements to enhance practical learning.

Additionally, the requirements were identified (see Table I) to guide the software design, distinguishing between those related to the system's core functionalities and those establishing technical conditions aimed at ensuring application performance, usability, and accessibility. These requirements enabled the definition of the main functionalities, technical constraints, and system quality criteria, thereby structuring the development process in an organized manner. Furthermore, the identification of requirements facilitated alignment of the software with end-user needs.

TABLE I. SYSTEM REQUIREMENTS

ID	Requirements
R1	The application shall display interactive 3D models of automotive components.
R2	The application shall provide short, dynamic lessons (5–10 minutes) covering specific automotive maintenance concepts.
R3	The application shall enable fast navigation between modules, allowing technicians to access the sections they need to study.
R4	The application shall be user-friendly and intuitive.

B. Initialization Phase

During the Initialization phase, the technical elements that would structure the mobile application were defined, establishing a solid foundation for its subsequent development. Programming tools, development environments, and graphics engines were selected to implement the planned functionalities, ensuring efficient integration of educational content with Augmented Reality (AR) resources. Fig. 1 illustrates the set of components and tools selected for the system's initial architecture.

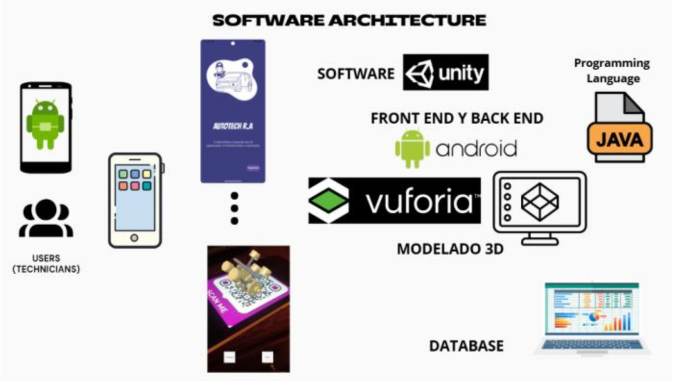


Fig. 1. System architecture.

During the subsequent stage, the overall system architecture (Fig. 1) was structured, considering the different modules that would compose the application. Unity 3D was selected as the primary development environment due to its capability to manage three-dimensional graphical environments and its compatibility with Augmented Reality (AR) tools. For the visualization of augmented objects, the Vuforia engine was integrated, enabling image recognition and the projection of digital models onto real-world markers.

The system logic was developed using C#, a programming language that facilitated dynamic interaction between objects and graphical components. In parallel, Java was utilized to ensure software compatibility with the Android operating system. Additionally, a simple data storage structure was implemented to record user performance information, including assessment results and satisfaction survey responses.

The design also focused on providing intuitive navigation that was accessible and aligned with the needs of the target audience: technical training technicians. A clean visual layout, direct-access buttons, and clear typography adapted to different screen sizes were prioritized. Furthermore, usability and user experience (UX) principles were considered, including the reduction of cognitive load, consistency in graphical elements, and visual feedback in response to user actions.

C. Production Phase

During the Production phase, all components that shaped the functional structure of the Augmented Reality (AR)-based mobile application were developed and integrated. This stage represented a critical milestone, as it enabled the transformation of previously identified technical and pedagogical requirements into interactive and operational modules aimed at enhancing the user's learning experience. The focus of this phase was to combine immersive technology with instructional design principles (see Table II) to build an accessible, functional, and pedagogically effective tool aligned with the needs of technicians in training.

Various thematic modules were designed and implemented, focusing on fundamental components of automotive maintenance, such as engines, valve trains, crankshafts, pistons, suspension systems, among others. Each module was structured to allow users to access essential theoretical content supported by high-quality graphical representations and interactive three-dimensional models.

TABLE II. PRODUCTION PHASE COMPONENTS

ID	Description
Developed Modules	Engines, valve train systems, crankshafts, pistons, and braking systems
Technical Content	Visual and textual guides integrated into each module
Interactive Resources	3D models, animations, navigation buttons, and QR codes
Functional Logic	Modular flow organized by thematic levels, incorporating touch-based and visual interaction
Technical Validation	Review conducted by automotive industry professionals
AR Integration	Linking 3D models to visual markers for augmented visualization

The development of these modules followed a user-centered approach. The development team built the application to be intuitive, clear, and fluid, enabling participants to move easily between content sections. The main interface of the application, shown in Fig. 2 and 3, presents an organized view of the available modules, where each option is accompanied by a representative image and a direct-access button. The interface is presented in Spanish, as the application was developed for a Spanish-speaking technical education context. The visual layout allows users to quickly identify topics, promoting autonomous access to the learning materials.

Upon entering each module, as shown in Fig. 4, users were presented with a general introduction to the topic, followed by a detailed description of the system components, their operation, and maintenance procedures. This information was delivered through simplified technical text, designed to be reinforced through the exploration of Augmented Reality (AR) models, which responded to interaction commands such as rotation, zooming, and perspective changes.

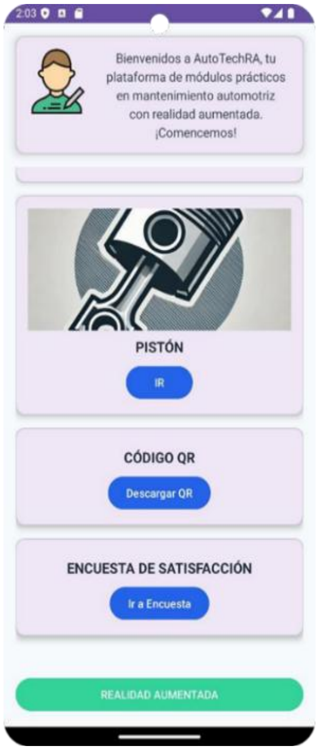
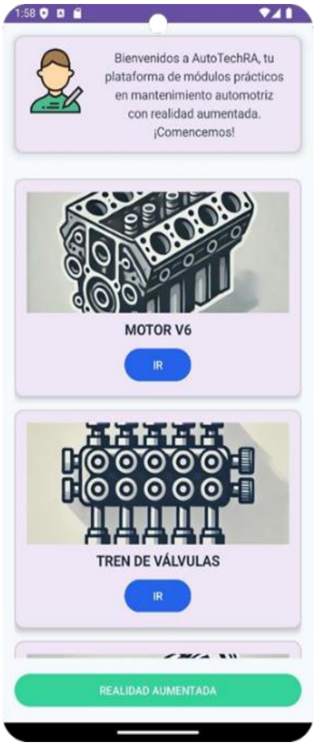

Bienvenidos a AutoTechRA, tu plataforma de módulos prácticos en mantenimiento automotriz con realidad aumentada. ¡Comencemos!

Fig. 2. Main menu interface.



Bienvenidos a AutoTechRA, tu plataforma de módulos prácticos en mantenimiento automotriz con realidad aumentada. ¡Comencemos!

Fig. 3. Main menu interface layout.

Capacitación: Motores V6

Una guía completa sobre los motores V6: diseño, características, ventajas y aplicaciones.

Introducción

Un motor V6 es un motor de combustión interna con seis cilindros dispuestos en forma de V. Este diseño se caracteriza por su equilibrio entre potencia, tamaño compacto y eficiencia, lo que lo convierte en una opción popular para automóviles, SUV y camiones ligeros. A lo largo de esta capacitación, exploraremos en detalle cómo funcionan los motores V6 y por qué son una de las configuraciones más versátiles en la industria automotriz.

Diseño y Arquitectura

1. **Configuración en V**: Los cilindros se colocan en dos bancos inclinados a un ángulo de 60° o 90°, formando la letra 'V'. Esto permite un diseño compacto que es ideal para vehículos de tamaño mediano.

2. **Cigüeñal compartido**: Utiliza un cigüeñal compartido para reducir la complejidad del motor y mejorar el equilibrio dinámico.

3. **Relación peso-potencia**: Su diseño compacto resulta en una relación peso-potencia eficiente, lo que lo hace competitivo frente a los motores en línea o V8.

Ventajas de los Motores V6

1. **Compactos**: Ocupan menos espacio en el compartimento del motor en comparación con los motores en línea.

2. **Suavidad**: Ofrecen un buen equilibrio entre potencia y suavidad gracias a su diseño.

3. **Versatilidad**: Pueden ser utilizados en una amplia gama de vehículos, desde sedanes hasta SUVs.

4. **Eficiencia**: Su diseño permite un mejor consumo de combustible en comparación con motores más grandes como los V8.

Aplicaciones Comunes

1. **Automóviles de pasajeros**: Sedanes y coupes de tamaño mediano a grande.

2. **SUVs**: Su equilibrio entre potencia y economía los hace ideales para SUVs compactos y medianos.

3. **Camiones ligeros**: Son una opción popular en camiones de tamaño mediano, ofreciendo capacidad de remolque moderada sin sacrificar eficiencia.

4. **Deportivos**: En vehículos deportivos, los V6 se utilizan por su capacidad para generar altas revoluciones y buena potencia.

Fig. 4. Module information interface.

From a pedagogical perspective, the design prioritized visual clarity, logical content progression, and the sequential execution of learning activities. Animations and intuitive navigation controls were incorporated to enable smooth transitions between modules, thereby reinforcing learning continuity. Additionally, complementary resources were integrated to enrich the in-app navigation experience and strengthen the connection between visual and conceptual content.

Among the implemented resources, navigational buttons (Fig. 5 and 6) were strategically positioned to facilitate movement between sections, allowing users to advance, return, or restart each module without difficulty. This functionality was specifically designed to ensure user autonomy during the learning process, reducing the need for external assistance and promoting independent exploration of the content.

Fig. 5. AR-based 3D visualization of engine components.

Fig. 6. AR-based 3D visualization of brake system components.

Finally, the inclusion of a QR code (Fig. 7) aimed to promote learner autonomy by enabling technicians to review content at different times and across various devices. This functionality proved particularly useful for reinforcing key concepts, visualizing procedures from different perspectives, and accessing reliable resources through a single scan using the mobile device camera.

Continuous validation was conducted with automotive industry specialists, who reviewed the technical accuracy of the models and the content presented in each module. Adjustments were also made to the user interface (UI) and user experience (UX) components to ensure coherent, accessible navigation aligned with the characteristics of the target audience. In summary, the Production phase resulted in the consolidation of an operational version of the application, composed of complete thematic modules, integrated Augmented Reality (AR) functionalities, and a user-centered design.

Descarga tu Código QR

Este código QR contiene diferentes diseños 3D interactivos para ser visualizados en realidad aumentada. Presiona el botón a continuación para acceder al archivo en Google Drive y descárgalo.

Instrucciones:

1. Presiona el botón para abrir el enlace de Google Drive.
2. Descarga el archivo en tu dispositivo.
3. Imprime el código QR y úsalo con nuestra aplicación de realidad aumentada.

Nota: Necesitas conexión a internet para acceder a Google Drive. Si tienes problemas, contacta con el soporte técnico.

Fig. 7. User interface for content access.

D. Stabilization Phase

The Stabilization phase aimed to ensure that the developed mobile application operated correctly, stably, and efficiently before being deployed to end users. During this stage, the team conducted rigorous internal testing to identify technical errors, verify system performance, and optimize the user experience under different operational conditions. The evaluation focused on aspects such as 3D model loading time, stability of core functionalities, navigation fluidity between modules, and system responsiveness across different mobile devices.

These tests enabled the identification of necessary adjustments, including graphic resource compression, animation optimization, and code debugging to prevent potential failures or performance slowdowns during execution. The application's behavior when interacting with Augmented Reality (AR) elements was also evaluated. Performance and robustness testing was conducted on Android and iOS mobile devices, recording an average initial loading time of 3.5 seconds, RAM usage of approximately 250 MB, and AR interaction response times under 2 seconds. QR marker recognition and 3D model projection were evaluated under the indoor lighting conditions typical of an automotive workshop environment, confirming stable tracking performance across the tested devices.

Finally, the phase concluded with an optimized application ready for evaluation in a real-world environment. The actions undertaken during this stage were essential to prevent errors during field use and to ensure a positive educational experience based on mobile technology and Augmented Reality (AR). Additionally, preliminary functional tests were conducted to verify system stability, correct visualization of virtual objects, and appropriate interaction with AR markers.

V. RESULTS

A total of 60 automotive maintenance technicians participated in this study, with 30 assigned to the control group and 30 to the experimental group.

A. Level of Comprehension of Technical Content (NCC)

The assessment of the level of comprehension of technical content revealed marked differences between the two groups. In the control group, participants were predominantly categorized at the "Beginning" and "In Progress" performance levels. Conversely, the experimental group showed a higher concentration of participants at the "Expected Achievement" and "Outstanding Achievement" levels. The Shapiro–Wilk normality test indicated that the data did not follow a normal distribution in either group (Control Group: $p = 0.024$; Experimental Group: $p = 0.029$). Due to this non-normal distribution, the non-parametric Mann–Whitney U test was employed for group comparison. The test yielded a p-value of 0.001 (at a 95% confidence level), indicating a statistically significant difference between the control and experimental groups regarding the level of comprehension of technical content. Furthermore, the effect size calculated using Rosenthal's r coefficient yielded $r = 0.86$, indicating a large practical effect and confirming that the observed differences were not only statistically significant but also educationally meaningful.

B. Average Training Time (ATT)

The Average Training Time (ATT) differed substantially between groups. The control group technicians required an average of 10,862 seconds (approximately 181 minutes) to complete all training activities. The experimental group technicians completed the same activities in an average of 5,784 seconds (approximately 97 minutes), representing a reduction of 5,078 seconds, or 46.6% less time than the control group. Shapiro–Wilk testing revealed non-normal data distribution (Control Group: $p < 0.001$; Experimental Group: $p = 0.054$). The Mann–Whitney U test comparing both groups of participants yielded a p-value of 0.001, establishing statistical significance at the 95% confidence level. This reduction in training duration occurred while maintaining the same training objectives and assessment criteria across both groups. The effect size analysis yielded $r = 0.87$, indicating a large practical effect and confirming that the reduction in training time represented a substantial and meaningful improvement beyond statistical significance (Table III).

TABLE III. SUMMARY OF STATISTICAL RESULTS FOR PRIMARY INDICATORS

Metric / Group	**NCC^1**	**ATT^2**	**NCS^3**
Control Group	Beginning / In Progress	10,862 s (≈)	M = 2.6 (5-point scale)
Experimental Group	Expected Achievement / Outstanding Achievement	5,784 s(≈97min)	M = 4.0 (5-point scale)
p-calue	P = 0.001	P = 0.001	P = 0.001
Effect Size (Rosenthal's r)	0.86 (large)	0.87 (large)	0.86 (large)
Result	Significant	Significant	Significant

C. Participant Satisfaction Level (NSC)

Satisfaction was measured on a 5-point Likert scale (1 = Very Dissatisfied; 5 = Very Satisfied). The control group technicians achieved a mean satisfaction score of 2.6, while the experimental group technicians obtained a mean score of 4.0. This 1.4-point difference represents a 54% increase in satisfaction levels in the experimental group compared to the control group. The Mann–Whitney U test comparing satisfaction levels between participants yielded a p-value of

0.001 (at a 95% confidence level), confirming a statistically significant difference in favor of the experimental group technicians.

The effect size calculated using Rosenthal's r coefficient yielded r = 0.86, indicating a large practical effect and demonstrating that the improvement in satisfaction levels was not only statistically significant but also of considerable practical relevance.

VI. DISCUSSION

As detailed in the Results section, the experimental group achieved significantly higher scores in the comprehension of technical content (NCC) and participant satisfaction (NSC), while reducing the average training time (ATT) by 46.6% (p = 0.001). Regarding the first indicator, the level of comprehension of technical content (NCC) showed a marked improvement in the experimental group that utilized the Augmented Reality (AR) application. In contrast, the control group remained predominantly at performance levels categorized as "Beginning" and "In Progress," whereas the experimental group reached higher levels such as "Expected Achievement" and "Outstanding Achievement," confirming a statistically significant difference between groups. The large effect size obtained (r = 0.86) further supports the educational relevance of these differences, indicating that the AR-based intervention produced a substantial improvement beyond mere statistical significance. These findings highlight that the immersive and interactive nature of AR-based tools enhanced the assimilation of complex technical content, allowing technicians to develop a deeper conceptual understanding than that achieved through conventional training methods.

These results are consistent with prior studies, such as Aoufy Khadija et al. [20], which demonstrated that participants trained using immersive technologies—like AR and Virtual Reality (VR)—achieved significantly higher post-training assessment scores. This evidence reinforced the positive impact of immersive technologies on knowledge retention, comprehension, and practical application.

Moreover, within the context of this study, the incorporation of interactive and immersive environments promoted active technician participation, increased motivation for learning, and facilitated the visualization of complex concepts that are difficult to grasp through traditional methods. These findings suggest that integrating AR-based tools may represent a promising pedagogical strategy to improve technical training outcomes, although further research is needed to confirm these effects in broader educational contexts.

Concerning the second indicator, Average Training Time (ATT), the experimental group demonstrated a substantial improvement in efficiency, completing the training activities in significantly less time than the control group. This improvement suggested that the structured, module-based design of the AR application—which allowed technicians to interact directly with three-dimensional representations of automotive components—reduced the cognitive effort required to understand procedural sequences, thereby accelerating task completion without compromising learning quality. The effect size analysis (r = 0.87) confirmed that this reduction was not only statistically significant but also of large practical magnitude, reinforcing the efficiency gains attributed to the AR-based intervention.

These findings aligned with the study conducted by Yıldırım and Yıldırım [8], which reported that AR and VR technologies reduced the time needed to complete complex technical tasks by 10% to 15%, attributed to direct and detailed visualization of processes, three-dimensional component representation, and the superimposition of digital information onto the physical environment.

Additionally, within this study, immersive tools enabled participants to interact with virtual models in real time, strengthening procedural and cognitive skill acquisition. These results suggest that AR-based applications may contribute to improving training efficiency, though generalization to broader professional settings requires further investigation.

Finally, regarding technician satisfaction (NSC), a clear difference emerged between groups. While the control group reported predominantly low satisfaction scores, the experimental group achieved a mean score of 4.0 on a 5-point Likert scale, reflecting a statistically significant improvement (p = 0.001). The large effect size (r = 0.86) confirmed that this improvement was of considerable practical relevance, not merely a statistically detectable difference. This outcome demonstrated that the immersive and autonomous nature of AR-based training positively influenced user perception, fostering engagement and motivation. Previous studies, such as Ojer et al. [21], supported these results, showing that immersive environments increased perceived usability and motivation, with satisfaction levels reaching up to 90% compared to approximately 65% for traditional teaching methods.

Interaction with virtual and augmented environments also enhanced engagement, sustained attention, and positive perceptions of the learning process, which translated into a greater willingness to acquire technical knowledge and develop practical skills. Consequently, the integration of immersive technologies in technical training programs represented an innovative strategy with strong potential to optimize learning effectiveness and enhance user experience.

Overall, the implementation of the AR-based mobile application produced statistically significant improvements across all three evaluated indicators: comprehension of technical content, training efficiency—with a 46.6% reduction in average time—and participant satisfaction (p = 0.001 for all cases). These outcomes suggest that, within the context of this study, AR-based tools not only optimized instructional processes but also enhanced motivation and engagement among technicians, indicating a positive influence on learning quality and willingness to acquire new technical competencies.

The incorporation of immersive technologies promoted an interactive and user-centered learning experience within the evaluated training context. These findings suggest that AR-based mobile applications may contribute to aligning technical training with contemporary industry demands, though broader conclusions regarding industry-wide impact would require studies conducted across more diverse organizational and regional settings.

Despite these promising findings, the study presented several limitations. First, the sample was drawn from a single automotive company in Trujillo, Peru, which may limit the generalizability of the results to technicians working in different organizational contexts, training environments, or regions. Second, the study did not assess long-term knowledge retention, leaving uncertain whether the observed learning gains persisted over time. Third, outcomes may have been partially influenced by novelty effects associated with the introduction of new technology, potentially inflating initial motivation and satisfaction scores. Fourth, although the application was tested across multiple device models, robustness testing was limited to indoor workshop lighting conditions, without evaluating marker-based AR performance under varying illumination or outdoor environments. Future research should address these limitations by incorporating larger and more diverse samples across multiple organizations, longitudinal follow-up assessments, control conditions that account for novelty effects, and robustness testing across diverse environmental settings.

VII. CONCLUSION

Regarding the level of technical content comprehension, it was concluded that the use of the Augmented Reality (AR)-based mobile application significantly enhanced learning outcomes among automotive maintenance technicians. The group that utilized the application predominantly achieved performance levels categorized as “Expected Achievement” and “Outstanding Achievement,” in contrast to the group that did not use the tool. This difference was statistically supported by the Mann–Whitney U test (p = 0.001), allowing acceptance of the alternative hypothesis at a 95% confidence level and suggesting that, within the context of this single-company study, the implemented technology had a positive impact on the assimilation of complex technical content, though these findings should be interpreted with caution given the limited deployment scope.

Regarding the average training time, a notable improvement in efficiency was observed. The experimental group completed the training sessions in an average of 5,784 seconds, whereas the control group recorded 10,862 seconds. This 46.6% reduction in training time suggests that the application optimized the instructional process without compromising learning quality under the conditions of this study, though longitudinal validation would be needed to confirm sustained efficiency gains. The statistical significance of this difference was validated through the Mann–Whitney U test (p = 0.001), providing statistical evidence that the technological implementation reduced training duration within the evaluated context.

Regarding participant satisfaction, a considerable increase was observed. The group that used the application reported higher satisfaction levels, achieving a mean score of 4.0 on a 5-point scale, whereas the control group obtained an average of 2.6 points. These results reflect not only improved reception of the training process but also greater motivation and engagement among the technicians. As in the previous indicators, the difference was statistically significant (p = 0.001), reinforcing the conclusion that, within this study's context, the AR-based educational approach was positively received by participants, though broader adoption would require validation across more diverse training environments and longer evaluation periods.

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