# Augmented Reality-Based Simulation for Project Based Learning-Troubleshooting (PjBL-T) on Automotive Chassis Course

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***Abstract*—This study integrates an Augmented Reality (AR) simulation into a Project-Based Learning–Troubleshooting (PjBL-T) model for an automotive chassis course to strengthen students' diagnostic and problem-solving skills. Using a developmental research design, we applied a 4D sequence—Define including needs analysis and task/specification mapping, Design including AR storyboard, PjBL-T syntax alignment, instrument blueprints, Develop including prototype builds, expert validation, small-group try-out, and Disseminate including field implementation and refinement. Participants were purposively sampled from intact classes enrolled in the course which are one PjBL-T+AR cohort and a comparison cohort using conventional media. The AR module using Unity engine with Vuforia SDK delivered manipulable 3D models of suspension, steering, and braking systems and included parameterized virtual-fault scenarios for guided troubleshooting. Data were gathered with a diagnostic-accuracy rubric, a problem-solving performance rubric, a concept comprehension test, and a student engagement survey (Likert). Analyses included content validity, reliability checks, and inferential tests. Results show higher engagement, deeper conceptual understanding, and improved diagnostic accuracy for the PjBL-T+AR cohort relative to baseline and the comparison group. The model is scalable because it (i) runs on widely available Android smartphones/tablets with offline assets, (ii) uses modular, reusable fault libraries and glTF/FBX 3D packages that map directly to each PjBL-T stage, and (iii) provides templated authoring and Learning Management System (LMS) integration, enabling rapid replication across courses and institutions without specialized labs.**

***Keywords*—Augmented Reality (AR), Project-Based Learning–Troubleshooting (PjBL-T), automotive chassis education, vocational and technical education, Learning Management System (LMS) integration**

## I. Introduction

Successful learning not only facilitates the mastery of material, but also encourages behavioral change, the development of reasoning power, and the achievement of critical and creative thinking skills [1, 2]. The interaction between educators, students, and learning resources is the core of an effective and meaningful learning process [3]. At the higher education level, learning has a strategic role in shaping graduates who not only master knowledge, but also have problem-solving skills, creativity, and collaborative work abilities. Through various forms of activities such as lectures, seminars, discussions, and project assignments, students are given space to develop their academic and social potential. In this context, universities are responsible for preparing graduates who are adaptive to global challenges and the dynamics of the world of work [4].

The need for graduates with dynamic thinking emphasizes the importance of mastering Higher Order Thinking Skills (HOTS). A previous study [5] frames HOTS as involving analytical, evaluative, and creative abilities. Aligned with this perspective, developments in information technology have prompted a transition in learning—from manual skill practice to technology-oriented cognitive skill development [6]. Current and future professions demand the ability to access, manage and critically evaluate information.

The application of the right learning model not only helps in achieving learning objectives, but also provides systematic direction for lecturers and students in carrying out learning activities. Accordingly, the lecturer assumes the role of architect of learning experiences that align with learners' contexts, needs, and capacities [7]. One of the courses that requires the right learning approach is Automotive Chassis. This course not only requires mastery of technical concepts, but also systematic thinking skills and practice-based problem solving. Effective learning in this course should be able to provide a foundation for logical and structured thinking and the ability to identify and solve real problems in the automotive field. However, observations in the Automotive Engineering Education Study Program show that the learning process in the Automotive Chassis course is still conventional, lecturer-centered, and dominated by lectures. Students are less actively involved, thus reducing their absorption and motivation to learn. The learning media used has not been able to encourage in-depth understanding, which is reflected in the lack of student initiative in discussing or asking questions. Critical thinking skills and active participation still need to be improved so that the learning

experience becomes more significant and contextualized.

To strengthen learners' critical thinking and overcome PjBL's deficits, the Project-Based Learning–Troubleshooting (PjBL-T) model was developed, integrating PjBL with a methodical troubleshooting framework. Through this approach, students are required to actively identify real problems, explore solutions, and design projects collaboratively. Both approaches are oriented towards Student Centered Learning (SCL), where students are active in building their own knowledge through direct involvement in learning that is relevant to real world situations.

Establishing the PjBL-T approach is essential because it simultaneously promotes critical thinking, higher academic attainment, and stronger collaboration among students. This model not only deepens conceptual understanding, but also develops other skills such as problem solving, team collaboration, and communication. In particular, the troubleshooting approach helps to overcome some of the weaknesses of PjBL, especially in understanding the complexity of problems and improving the quality of collaborative interactions between students [8, 9].

Augmented Reality (AR)-based simulation has emerged as a powerful tool in modern technical education, particularly in vocational fields like automotive engineering. By overlaying digital information onto physical environments, AR allows students to interact with 3D models of complex mechanical systems in real-time. This technology enhances comprehension by providing visual and spatial understanding of components that are otherwise difficult to observe directly. In the context of automotive chassis learning, AR-based simulation enables students to explore suspension, steering, and braking systems without the need for physical disassembly. It also supports troubleshooting exercises by simulating various fault scenarios, allowing learners to practice diagnostic procedures in a risk-free environment. The integration of AR into Project Based Learning-Troubleshooting (PjBL-T) models promotes active, inquiry-driven engagement. Ultimately, AR-based simulation not only improves technical competence but also fosters critical thinking and problem-solving skills among automotive students.

Despite the recognized potential of PjBL-T and AR, there is a documented gap between (a) the complex diagnostic demands of Automotive Chassis and (b) the current lecture-dominated practices that limit student engagement, inquiry, and HOTS development. There is insufficient empirical evidence—within the Automotive Engineering Education Study Program—on whether an AR-enhanced PjBL-T design causally improves students' (1) diagnostic accuracy, (2) conceptual understanding of chassis systems, and (3) learning engagement relative to conventional instruction and to PjBL-T without AR support. Therefore, the problem addressed in this study is to design, implement, and evaluate an AR-based simulation integrated into the PjBL-T model and to determine its effectiveness in improving key learning outcomes in the Automotive Chassis course.

It is hypothesized that students in the experimental group—taught using Project-Based Learning with Technology (PJBL-T) integrated with Augmented Reality (AR)—will demonstrate significantly greater gains in critical thinking skills than students in the control group who receive non-PJBL-T instruction with AR. Specifically, the experimental group is expected to outperform the control group on posttest critical-thinking scores and normalized gains across the indicators of analysis, evaluation, inference, and problem-solving, after controlling for baseline (pretest) differences. The null hypothesis states that there will be no significant difference between groups on these critical-thinking outcomes.

Thus, the development and implementation of the Augmented Reality (AR)-based simulation for Project Based Learning-Troubleshooting model is very appropriate in learning Automotive Chassis in the Automotive Engineering Education Study Program. This model is expected to increase student competence in thinking critically, creatively, working together, and communicating effectively, thus producing graduates who are competent, adaptive, and ready to face challenges in today's world of work.

Across education broadly, meta-analyses and systematic reviews converge that AR tends to yield small-to-moderate improvements in learning outcomes and motivation, while flagging recurring usability and cognitive-load issues. Akçayır & Akçayır's Computers & Education [10] review synthesizes gains alongside design pitfalls; Bacca *et al.* [11] document early education AR trends; and Garzón *et al.* [12] estimate a medium overall effect on achievement. More recently, vocational-specific syntheses show AR's strong utility for skills training. Chiang *et al.* [13] review AR in vocational training, and Liu *et al.* [14] map virtual reality/augmented reality models and outcomes in vocational education technology underscoring benefits for procedural guidance and safe practice in high-stakes, equipment-intensive contexts.

Project-Based Learning (PjBL) itself is well-supported: a large meta-analysis finds significant positive effects of PjBL on student achievement across two decades of studies, including STEM contexts. Yet most AR-enhanced PjBL reports remain short-duration pilots or single-group designs, often conflating the effect of the medium (AR) with the method (PjBL) and rarely measuring critical thinking or diagnostic accuracy with validated instruments. In addition, fidelity monitoring and blinded scoring are seldom reported, limiting causal claims about why outcomes improve [15, 16].

This study advances both theory and method by operationalizing a hybrid PjBL-Troubleshooting (PjBL-T) model integrated with AR and testing it under rigorous experimental conditions in a vocational automotive context. Conceptually, we specify how troubleshooting cycles are embedded within PjBL stages, and why AR's affordances should amplify the analysis and evaluation–inference components of critical thinking. Methodologically, we isolate pedagogy from technology by giving both groups access to AR while randomizing intact classes to PjBL-T+AR versus non-PjBL-T+AR. We pair this design with multi-domain outcomes, blinded scoring, and fidelity checks—providing a replicable template for causal claims about instructional mechanisms rather than media novelty.

Practically, the work delivers a scalable implementation stack: offline-capable Unity/Vuforia assets that run on commodity Android devices; a modular virtual-fault library mapped to each PjBL-T phase; and templated artifacts that

reduce instructor preparation time and ease Learning Management System (LMS) integration. This combination addresses a common gap in prior AR/PjBL reports—namely, limited portability beyond well-resourced labs—by demonstrating low-infrastructure deployment across an eight-week course with matched facilities. The result is a generalizable design pattern that institutions can adapt to other automotive domains and to broader TVET settings where critical thinking and troubleshooting are core graduate outcomes.

## II. Literature Review

### A. Development of Project Based Learning-Troubleshooting (PjBL-T) Model

This study aims to design a Project Based Learning-Troubleshooting (PjBL-T) learning model specifically designed to improve students' critical thinking skills in the Automotive Chassis course of the Automotive Engineering Education Study Program. This learning model integrates the Project and the troubleshooting process so that students can develop conceptual knowledge as well as practical skills.

In the context of constructivistic learning, students are seen as active agents who build understanding through real experiences. Empirical studies show that curricula that are too fixated on material coverage often neglect the development of critical thinking, while many educators still use direct instructional methods that hinder students' analytical skills [10]. Therefore, the application of PjBL-T offers a framework that emphasizes active engagement, where students not only learn theoretical concepts, but also apply them to solve real technical problems.

The present research aims to design a PjBL-T learning model specifically targeted at enhancing critical thinking among students in the Automotive Chassis course of the Automotive Engineering Education Study Program. By integrating project activities with systematic troubleshooting, the model advances conceptual knowledge alongside hands-on skills.

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### B. Characteristics of Automotive Chassis Course

D. Tanner and L. N. Tanner [18] suggested that curriculum constitutes the systematic orchestration of educational experiences at schools and universities, affording students opportunities to broaden knowledge, acquire skills, and cultivate attitudes, interests, and values. It comprises multiple planning documents—varied in form and depth—that specify the intended learning experiences [19]. Therefore, within the enacted system, the university designs the curriculum to secure attainment of the stated learning outcomes (Table 1).

In the Automotive Engineering Education Study Program, FT UNIMED, the Automotive Chassis curriculum is developed to cultivate knowledge, skills, and the enactment of appropriate attitudes. Instruction centers on braking, steering, and suspension systems, alongside the interlinking mechanisms that unite these areas in motorized vehicles. The curriculum aims to graduate students who possess strong chassis expertise and practical competence and who, guided by scientific dispositions and foundational values, can make informed decisions, resolve automotive problems, and contribute to program learning.

Table 1. Characteristics of the automotive chassis course

| Variable | Characteristics |
|---|---|
| **Attitude** | • Interest in vocational education<br>• Cooperation in learning, discipline, commitment, responsibility, communication, mutual cooperation, discipline, confidence, and interest in learning<br>• Attitude to Automotive Chassis |
| **Skill** | • Work safety<br>• Use of tools<br>• Perform fault analysis and diagnosis<br>• Perform repair and maintenance<br>• Problem solving<br>• Reporting and analyzing data |
| **Knowledge** | • Expertise related to manual/conventional and power-assisted steering; hydraulic braking and parking brakes; ABS; disc/disk brake mechanisms; brake boosters, including air-servo types; independent, rigid, and active suspension systems; and wheels.<br>• Understand and appreciate scientific facts, models and theories for the above systems.<br>• Able to use knowledge to solve problems in motor vehicles. |

Being a mandatory and principal course, the Automotive Chassis curriculum promotes comprehensive learner development across physical, emotional, spiritual, and intellectual dimensions. It rests on a synthesis of knowledge, scientific proficiency, and scientific attitudes anchored in core values, and is continually refreshed to keep pace with program aims and rapid technological change, shaping creative, innovative, and critically minded students.

Automotive Chassis is one of the effective courses offered to all students in the first year and is a Creative Proficiency Course (MKB) for the Automotive Engineering Education Study Program. This course is taught for only one semester to second year students and it is hoped that students can understand the concepts and principles of Automotive Chassis in more depth and their application in carrying out repairs and maintenance on motorized vehicles. This course was also developed to provide students with important knowledge to study other courses such as Vehicle Maintenance, Vehicle Testing, Field Practice Experience, and Thesis. Therefore, it is very important to formulate that the Automotive Chassis Course is an important scientific field that is dynamic and contributes a lot towards a broader mastery of Automotive Engineering. Improving student learning achievement from a qualitative point of view in all courses in the Automotive Engineering Education Study Program is a goal in an effort to improve and develop the quality of education.

### C. Augmented Reality-Based Simulation in Automotive Chassis

Augmented Reality (AR) combines real-world

surroundings with virtual elements. AR has been utilized for many different objectives in many different disciplines over the years. AR is employed as a reliable technology to do human jobs in nearly every sector. AR has proven to be helpful in increasing task accuracy and efficiency, particularly in the fields of surgery and aircraft production [20]. It is utilized in practically every industry, including education, entertainment, gaming, and more.

AR technology has been implemented in production settings by automakers for operations including inspection, maintenance, and assembly. When combined with other technologies, such as telepresence systems, AR can help with routine operations by offering operators support through various forms of information overlay in the workplace [21]. Additionally, technicians can deploy AR-based solutions that save learning time and mental effort by providing on-site instructions (right in front of their eyes) regarding the technique they need to follow [22] for car diagnostics and repair, including where and how to act [23]. As a result, even non-technical individuals may become mechanics by following the directions in AR programs to maintain their own vehicles [24], as well as by following 2D or 3D instructions on a mobile device [25].

Numerous augmented reality-based smartphone applications exist, including those for navigation, tourism and sightseeing, the military, marketing, and entertainment [26]. High-quality engineering education is necessary for modern science and technology. Creating a more interactive information-gathering system is a difficult problem. Thus, this problem is resolved by augmented reality technologies, which also offer an improved platform for interactive educational applications. Augmented reality is the fusion of the actual world with data from the 0 and 1 worlds. In real time, 2D and 3D models mix with real-world visuals to create a new, more engaging universe. Students in this day and age prefer visual and appealing learning methods than dull, lifeless texts. Furthermore, without any practical or visual aids, it is extremely challenging for students studying automotive engineering to comprehend the complex and sophisticated components of a vehicle's engine.

Because there is a lot of textual information and little visual representation, students, people working in the automotive industry, and anybody else who wants to learn more about any part of a vehicle' s engine—especially the inner and problematic sections of the inner parts—will not be able to find the precise information they are looking for. As a result, they cannot comprehend, and the information they do get will not enable them to engage with actual reality.

## III. Materials and Methods

### A. Development of Augmented Reality-Based Simulation in Automotive Chassis

Development of the AR application and accompanying learning package followed Branch' s ADDIE model [27] within an instructional R&D cycle [28]. In the Analysis phase, we conducted task and needs analyses for chassis diagnostics, mapped functional requirements, and audited Android device compatibility. The Design phase specified UML use cases, AR storyboards, troubleshooting flowcharts, and assessment blueprints. During Development, animations and videos were produced, user interfaces prepared, and all assets integrated in Unity 3D with Vuforia SDK for image/marker tracking, with offline packaging for low-bandwidth use. Implementation and Evaluation comprised pilot try-outs, expert review for content validity, and field testing for effectiveness.

The application' s performance, compatibility, and functionality were evaluated prior to deployment. The results of those tests show that the program functions properly, is compatible with many Android devices, and performs well in terms of memory and battery economy. Students that participate in corporate ethics training undergo implementation. Lastly, an assessment was required to determine whether behavioral simulations based on augmented reality improve students' moral imaginations.

### B. Project Based Learning-Troubleshooting in Chassis Automotive

The development of the Project Based Learning-Troubleshooting (PjBL-T) model in learning Automotive Chassis courses is carried out based on an instructional development research approach with a planning by objective paradigm, namely a development process that is systematically designed and directed at achieving predetermined learning objectives. The development procedure of this model is described through structured stages, including a detailed description of the characteristics of each development component and its function in each phase. In addition, the relationship between components is explained integratively so that the formation of the development system becomes synergistic and functional [28].

This research uses the Research and Development (R&D) method as the basic framework to design and develop a valid, practical, and effective PjBL-T learning model. The development process was carried out through three main stages. The first stage includes needs analysis activities and designing learning models that are relevant to the characteristics of the Automotive Chassis course. The second stage is directed at product validation and practicality testing, which aims to assess the feasibility and ease of implementing the model in a real learning environment. The third stage centered on assessing effectiveness by comprehensively evaluating how the PjBL-T model, when implemented, influenced learning outcomes, especially critical thinking, collaborative ability, and problem solving. This series of stages was designed to ensure that the PjBL-T model is not only theoretically relevant, but also applicable and able to improve the quality of vocational learning in the context of automotive engineering. A detailed visualization of the development flow is presented in Fig. 1. The preliminary research phase sought to collect all information required for model development through observations of existing models, identification of field problems, and a needs analysis.

Following the needs assessment, an initial PjBL-T prototype was constructed, including the preparation of core documents: the Semester Learning Plan (RPS), textbooks, a model guide, and implementation guidelines for lecturers and students. The design intentionally fuses Project-Based Learning with troubleshooting as a problem-solving approach for authentic automotive contexts. The conceptual

blueprint accounts for: 1) the learner cohort, 2) requisite infrastructure and facilities, and 3) targeted learning outcomes.

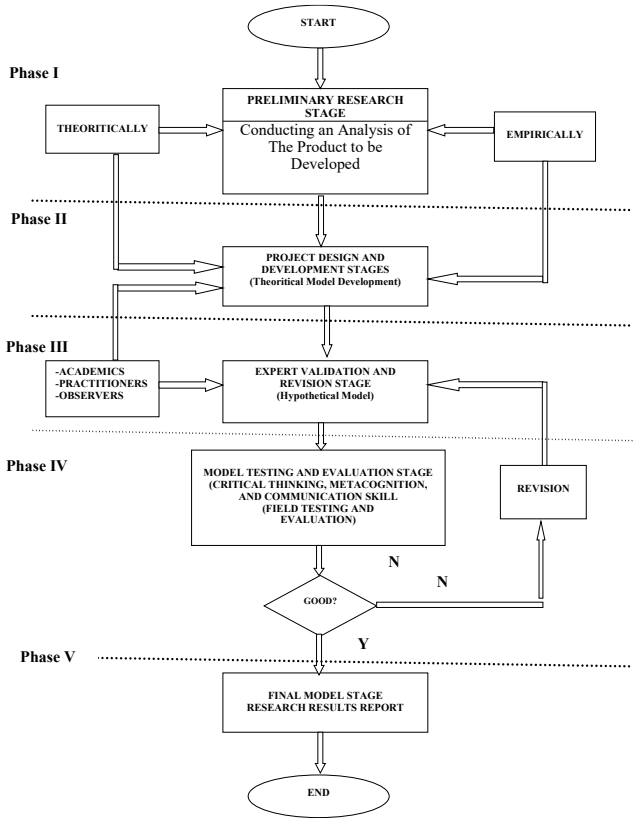


Fig. 1. Model development flow (adapted from Borg & Gall procedure).

This stage focuses on testing the substance and initial feasibility of the model by experts through Focus Group Discussion (FGD) techniques. Validation was carried out to assess aspects of clarity, integration of components, and suitability to learning objectives. Input from experts and lecturers was used to improve the product design. Expert validation was conducted through expert judgment which was planned to consist of six respondents. Respondents were drawn from three expert groups: vocational education, instructional design/learning, and content expertise. Validation additionally covered the syllabus, teaching resources, and evaluation instruments. This process not only ensures that the model is feasible to use, but also able to answer practical learning needs in the field systematically and effectively.

To reduce confounds, the same instructor taught both groups with standardized lesson plans and matched time-slots, rooms, toolkits, and identical AR builds. Implementation fidelity was monitored using an observer checklist administered twice per project cycle (target $\kappa \geq 0.70$). Baseline equivalence was checked on prior GPA, a chassis pretest, and a critical-thinking pretest; these scores were used to compute individual gain (post–pre) and normalized gain (g) for confirmatory analyses, rather than entered as covariates. A baseline survey captured prior industry experience, simulation familiarity, and academic motivation for descriptive balance checks and sensitivity analyses. Practical-exam raters and artifact scorers were blinded to group. Missing data were handled via listwise deletion for mixed-ANOVA runs; as a sensitivity check, one-way ANOVAs on gain/normalized-gain used multiply imputed datasets when missingness exceeded 5%.

Two intact classes meeting identical eligibility criteria were cluster-randomized by an independent administrator to experimental or control conditions with blocking by instructor and time-slot; allocation was concealed until rosters locked. We verified baseline equivalence on GPA and pretests. To minimize selection bias and instructor effects, the same instructor taught both groups using standardized lesson plans and matched time, rooms, toolkits, and identical AR builds. Practical-exam raters and artifact scorers were blinded to group.

The intervention ran 8 weeks (16 meetings; ~100 minutes each). Experimental teams consist of 4–5 students completed three authentic projects—steering shimmy (60–80 km/h), brake pull/long pedal travel, and front-end clunk/uneven ride height—each cycling through: AR-assisted problem orientation and evidence capture; fault-tree and 5-Why hypothesis generation; test planning and evidence collection using parameterized AR fault scenarios; solution design and AR prototyping; verification against acceptance criteria; and structured reflection via a Diagnostic Report and brief post-mortem video. Weekly design critiques and micro-clinics supported procedural fluency. The control group used the same AR for instructor-led demonstrations and guided individual practice but did not conduct team projects, create fault trees, iterate hypothesis-test loops, or participate in design critiques; contact time, topics, and assessment windows were matched.

Cognitive achievement was measured using a Chassis Concept Inventory (30–40 items) blueprinted to course outcomes, with content validity established by expert review and internal consistency reported (KR-20/α). Psychomotor skill was assessed via OSPE-style stations scored with a 4-level analytic rubric by two trained raters; inter-rater reliability (ICC/κ) was computed. Affective engagement employed a Likert-type engagement scale validated via CFA (fit indices and α reported). Critical thinking was scored with a diagnostics-focused rubric applied to artifacts and to a scenario-based test, with dual rating and reliability checks. Collaboration used a peer-assessment instrument. Problem-solving/diagnostic accuracy was captured through scenario tasks scored for correctness, evidence completeness, and decision-path efficiency.

Primary inference used a 2 Group: PjBL-T+AR vs non-PjBL-T+AR × 2 Time: pre vs post mixed-design ANOVA for each outcome, with the Group × Time interaction as the test of effectiveness. Assumptions were examined via Shapiro–Wilk and Levene's test; sphericity does not apply with two time levels. When homogeneity was violated, we report Welch's ANOVA for one-way follow-ups and robust CIs. As a confirmatory approach that addresses baseline differences without covariates, we conducted one-way ANOVAs on gain and normalized gain (g) comparing groups. For significant omnibus tests, Bonferroni-adjusted post-hoc comparisons were applied. We report $F$, $df$, $p$, partial $\eta^2$ and Hedges' g with 95% CIs. Familywise error across multiple outcomes was controlled using Benjamini–Hochberg FDR at $q = 0.05$.

The trial was conducted to collect data which was later used as a basis for determining the feasibility of the product

developed. The product in the form of a PjBL-T model for learning Automotive Engineering Education Study Program is tested on the subject to be tested. The conceptual model after passing expert judgment is then revised. Revisions are made to conceptual models that are less clear, for example, they are still mixed up between models, procedures and research instruments and final targets. After revising the conceptual model, it became a hypothetical model. Expanded field trials to see the effectiveness of the PjBL-T model compared to other learning models. At this stage, the learning model will be tested in the Automotive Chassis course. An extended trial was conducted with two cohorts: a control group and an experimental group using the PjBL-T model. Effectiveness was evaluated in terms of competency achievement, focusing on improvements in cognitive, affective, and psychomotor learning outcomes and their ancillary impacts. The concluding phase produced the final PjBL-T Model, which has undergone empirical testing and is intended to be valid, practical, and effective in higher-education automotive engineering contexts.

## IV. Result and Discussion

The study used a two-group quasi-experimental design with 48 students: 24 in the experimental group and 24 in the control group. The experimental group was taught using Project-Based Learning with Technology (PjBL-T) integrated with Augmented Reality, while the control group received instruction through non-PjBL-T with Augmented Reality. Both groups were given a pretest to measure their initial critical thinking abilities before the intervention. After the instructional treatment, a posttest was administered to assess improvements in critical thinking. The data collected from both pretest and posttest scores were then analyzed using normality tests, Levene's Test for homogeneity of variances, and ANOVA to test the research hypothesis. This design allowed for a clear comparison of the effectiveness of PjBL-T with Augmented Reality compared to conventional instruction.

Although the internal validity of the experiment is strengthened by cluster randomization, matched delivery, and blinded scoring, the sample is small (two intact classes; $N = 48$; ≈ 24 per group). With this size, a two-tailed $\alpha = 0.05$ comparison has ~80% power only for large effects approximately Hedges'/Cohen's $d \approx 0.80$–$0.85$, ~60–70% power for $d \approx 0.60$–$0.70$, and is underpowered for medium effects $d \approx 0.50$. For the mixed 2 × 2 ANOVA, assuming a typical pre–post correlation around 0.50, 80% power corresponds roughly to a Group×Time effect of partial $\eta^2 \approx 0.10$–$0.12$. In our data, the posttest contrast was large $F(1,46) = 14.97$, $p < 0.001$; partial $\eta^2 \approx 0.25$; Hedges' $g \approx 1.10$, which exceeds these thresholds; however, the modest N still implies wider confidence intervals and limited sensitivity to smaller, yet educationally relevan.

External validity is likewise constrained. Because only two clusters from a single institution were randomized, the effective degrees of freedom at the class level are minimal, and any class-specific or instructor-specific features cannot be fully separated from treatment effects (the intraclass correlation, ICC, was not estimated with precision under $k = 2$ clusters). Classroom conditions, student demographics, device profiles, and curricular pacing were matched here; thus, generalization should be limited to similar TVET/automotive contexts with comparable resources and an 8-week dosage.

The normality of the pretest scores was first examined using both the Kolmogorov-Smirnov and Shapiro-Wilk tests as shown in Table 2. For the PjBL-T group, the Kolmogorov-Smirnov significance value was 0.200 and the Shapiro-Wilk significance value was 0.096. For the Non-PjBL-T group, the Kolmogorov-Smirnov significance value was 0.191 and the Shapiro-Wilk significance value was 0.437. Since all significance values were greater than 0.05, the results indicate that the data from both groups were normally distributed. This finding confirms that the assumption of normality was satisfied for the pretest scores. With normal distribution established, the analysis could proceed with parametric statistical tests. Ensuring normality strengthens the validity of the subsequent ANOVA analysis, as one of its basic assumptions was fulfilled.

Table 2. Test of normality of pretest between PjBL-T and non-PjBL-T class

| | | Kolmogorov-Smirnov | | | Shapiro-Wilk | | |
|---|---|---|---|---|---|---|---|
| | Class | **Statistic** | ***df*** | **Sig.** | **Statistic** | ***df*** | **Sig.** |
| Pretest | PjBL-T | 0.136 | 24 | 0.200 | 0.930 | 24 | 0.096 |
| | Non-PjBL-T | 0.147 | 24 | 0.191 | 0.930 | 24 | 0.437 |

*df* = Degrees of Freedom; Sig. = Significance Value

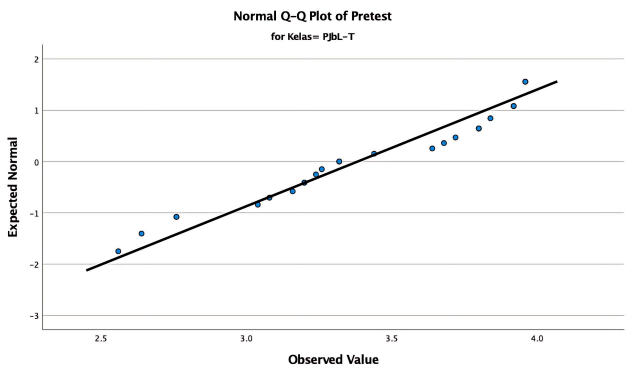


Fig. 2. Normality plot of pretest score of PjBL-T class.

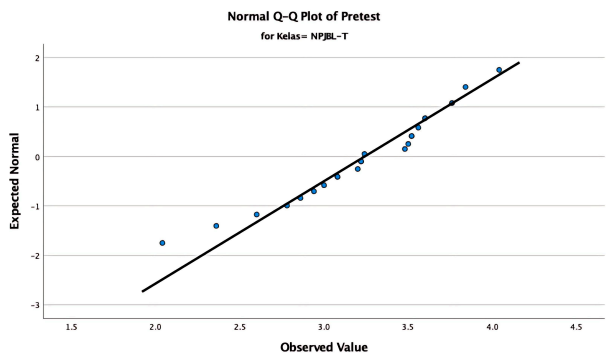


Fig. 3. Normality plot of pretest score of non-PjBL-T class.

The comparison of the Q-Q plots for the pretest scores of the PjBL-T and Non-PjBL-T classes demonstrates differences in the degree of conformity to the normal distribution. The Q-Q plot for the PjBL-T class shows that while the data points generally align with the diagonal line, slight deviations are observed at both the lower and upper tails, indicating minor departures from normality as shown in Fig. 2. Conversely, the Q-Q plot for the Non-PjBL-T class reveals a closer alignment of data points along the diagonal line, with fewer deviations at the extremes, suggesting a stronger fit to the normal distribution as shown in Fig. 3.

These findings imply that the pretest scores of the Non-PjBL-T class exhibit a distribution more consistent with normality compared to the PjBL-T class, thereby offering stronger support for the use of parametric statistical analyses.

Before conducting the ANOVA test, the assumption of homogeneity of variances was examined using Levene's Test as shown in Table 3. The results showed that for the pretest, the significance value was 0.940, while for the posttest, the significance value was 0.638. Both values are greater than 0.05, indicating that the assumption of equal variances was met. This means that the distribution of scores between the group using PjBL-T with Augmented Reality and the group without PjBL-T with Augmented Reality were comparable in terms of variance. Meeting this assumption is important because it validates the use of ANOVA as a suitable statistical analysis. Without meeting this assumption, the ANOVA results could have been biased or misleading. Thus, the analysis proceeded confidently to test whether there were significant differences between the two groups.

Table 3. Test of homogeneity of variances between pretest and posttest scores

| | | Levene Statistic | *df*1 | *df*2 | Sig. |
|---|---|---|---|---|---|
| Pretest | Based on Mean | 0.006 | 1 | 46 | 0.940 |
| | Based on Median | 0.020 | 1 | 46 | 0.889 |
| | Based on Median and with adjusted df | 0.020 | 1 | 44.372 | 0.889 |
| | Based on trimmed mean | 0.007 | 1 | 46 | 0.933 |
| Posttest | Based on Mean | 0.224 | 1 | 46 | 0.638 |
| | Based on Median | 0.186 | 1 | 46 | 0.668 |
| | Based on Median and with adjusted df | 0.186 | 1 | 45.989 | 0.668 |
| | Based on trimmed mean | 0.240 | 1 | 46 | 0.626 |

*df* = Degrees of Freedom; Sig. = Significance Value

Pretest descriptives as shown in Table 4, the two groups started at comparable levels. The PjBL-T with AR group recorded M = 3.384, SD = 0.440, 95% CI [3.199, 3.570]; the non-PJBL-T with AR group recorded M = 3.242, SD = 0.483, 95% CI [3.038, 3.446]. Medians (3.32 vs 3.23) and 5% trimmed means (3.397 vs 3.263) closely match the means, indicating limited influence of outliers. Dispersion was similar (variances (0.193) vs (0.233); variance ratio ≈ 1.21; IQR 0.70 vs 0.63; ranges 1.40 vs 2.00). Shape indices support normality: skewness −0.306 SE 0.472 and −0.711 SE 0.472, kurtosis −0.998 SE 0.918 and 0.383 SE 0.918; all $|z| < 1.96$. A baseline one-way ANOVA confirmed no pre-intervention difference in critical thinking, $F = 1.142$, $p = 0.291$, and the pretest effect size was small, $g \approx 0.30$ (95% CI ([-0.27, 0.87]). Taken together—overlapping CIs, near-identical medians/trimmed means, comparable variance, normal shape statistics, and a nonsignificant ANOVA—these results meet parametric assumptions (normality, homogeneity) and establish baseline equivalence, justifying the subsequent ANOVA on posttest and gain outcomes.

Posttest performance shown in Table 4 favored the PjBL-T+AR group: $M = 3.9367$, SD = 0.5422, 95% CI [3.7077; 4.1656], median =3.84, trimmed mean = 3.9270 ($\approx n = 24$). The non-PJBL-T+AR group recorded $M = 3.3433$, SD = 0.5201, 95% CI [3.1237;3.5629], median = 3.38, trimmed mean = 3.3715 ($\approx n = 24$). Dispersion was comparable (variances 0.294 vs 0.270; variance ratio ≈ 1.09; IQR 0.92 vs 0.68). Shape indices indicate acceptable normality PjBL-T+AR: skew 0.308 [SE 0.472], kurtosis -0.776 [SE 0.918]; non-PjBL-T+AR: skew -0.624 [SE 0.472], kurtosis 0.327 [SE 0.918]; all $|z| < 1.96$. The mean difference was ΔM = 0.5934. A one-way ANOVA on posttest scores was significant, $F(1,46) = 14.97$, $p < 0.001$, partial $\eta^2 = 0.246$ (large). The corresponding Hedges' g for the posttest contrast was 1.10 (95% CI [0.49, 1.71]), indicating a large, practically meaningful advantage for PjBL-T integrated with AR over non-PjBL-T with AR.

The ANOVA test for the pretest scores yielded an F-value of 1.142 with a significance value of 0.291. Since the significance value is greater than 0.05, it can be concluded that there were no significant differences between the groups before the treatment was given. This result demonstrates that students from both the PjBL-T Augmented Reality group and the non-PjBL-T Augmented Reality group had equivalent critical thinking abilities at the beginning. In other words, the two groups started from a relatively similar baseline condition. Establishing the equivalence of groups at the pretest stage strengthens the validity of the subsequent findings. It ensures that any differences observed at the posttest can be attributed to the treatment rather than initial disparities. This foundation supports the hypothesis testing with stronger reliability.

At baseline the two groups were equivalent according to Table 4: the PjBL-T+AR class scored $M = 3.384$, SD = 0.440 $M = 3.384$, SD = 0.440 and the non-PjBL-T+AR class $M = 3.242$, SD = 0.483 $M = 3.242$, SD = 0.483; a pretest ANOVA confirmed no difference, $F(1,46) = 1.142$, $p = 0.291$, partial $\eta^2 = 0.024$, $F(1,46) = 1.142$, $p = 0.291$, partial $\eta^2 = 0.024$. After the intervention, the PjBL-T+AR group outperformed the control on the posttest, with a mean advantage of $\Delta M = 0.593$. The posttest ANOVA was significant, $F(1,46) = 14.969$, $p < 0.001$, partial $\eta^2 = 0.246$ $F(1,46) = 14.969$, $p < 0.001$, partial $\eta^2 = 0.246$, and the between-group effect size was Hedges' $g = 1.10$ $g = 1.10$ (95% CI [0.49, 1.71]), indicating a large, practically meaningful effect. Gains likewise favored PjBL-T+AR, and normalized gains showed the same pattern. Together, these statistics substantiate that integrating Project-Based Learning with Technology and Augmented Reality yielded substantially greater improvements in critical-thinking performance than AR-supported, non-PjBL instruction.

The ANOVA test for the posttest scores revealed an F-value of 14.969 with a significance value of 0.000. Because this significance value is less than 0.05, the result indicates a significant difference in students' critical thinking abilities between the two groups after the treatment as shown in Table 5. Specifically, the group that received PjBL-T with Augmented Reality showed greater improvement compared to the group that did not. This finding supports the hypothesis that PjBL-T combined with Augmented Reality has a stronger effect on enhancing students' critical thinking skills. The result highlights the effectiveness of integrating

innovative instructional approaches into the classroom. Furthermore, it demonstrates that technology-supported project-based learning can create meaningful learning experiences. Therefore, it can be concluded that the hypothesis is accepted, as there is a significant difference favoring students who used PjBL-T with Augmented Reality.

Table 4. Descriptive test result for pretest and posttest

| Class | | | | Statistic | Std.Erro |
|---|---|---|---|---|---|
| Pretest | PjBL-T | Mean | | 3.3842 | 0.8974 |
| | | 95% Confidence Interval for Mean | Lower Bound | 3.1985 | |
| | | | Upper Bound | 3.5698 | |
| | | 5% Trimmed Mean | | 3.3972 | |
| | | Median | | 3.3200 | |
| | | Variance | | 0.193 | |
| | | Std. Deviation | | 0.43964 | |
| | | Minimum | | 2.56 | |
| | | Maximum | | 3.96 | |
| | | Range | | 1.40 | |
| | | Interquartile Range | | 0.70 | |
| | | Skewness | | −0.306 | 0.472 |
| | | Kurtosis | | −0.998 | 0.918 |
| | Non-PjBL-T | Mean | | 3.2417 | 0.09859 |
| | | 95% Confidence Interval for Mean | Lower Bound | 3.0377 | |
| | | | Upper Bound | 3.4456 | |
| | | 5% Trimmed Mean | | 3.2630 | |
| | | Median | | 3.2300 | |
| | | Variance | | 0.233 | |
| | | Std. Deviation | | 0.48299 | |
| | | Minimum | | 2.04 | |
| | | Maximum | | 4.04 | |
| | | Range | | 2.00 | |
| | | Interquartile Range | | 0.63 | |
| | | Skewness | | −0.711 | 0.472 |
| | | Kurtosis | | 0.383 | 0.918 |
| Posttest | PjBL-T | Mean | | 3.9637 | 0.10616 |
| | | 95% Confidence Interval for Mean | Lower Bound | 3.7077 | |
| | | | Upper Bound | 4.16556 | |
| | | 5% Trimmed Mean | | 3.9270 | |
| | | Median | | 3.8400 | |
| | | Variance | | 0.294 | |
| | | Std. Deviation | | 0.54219 | |
| | | Minimum | | 3.08 | |
| | | Maximum | | 5.00 | |
| | | Range | | 1.92 | |
| | | Interquartile Range | | 0.92 | |
| | | Skewness | | −0.308 | 0.472 |
| | | Kurtosis | | −0.776 | 0.918 |
| | Non-PjBL-T | Mean | | 3.3433 | 0.10616 |
| | | 95% Confidence Interval for Mean | Lower Bound | 3.1237 | |
| | | | Upper Bound | 3.5629 | |
| | | 5% Trimmed Mean | | 3.3715 | |
| | | Median | | 3.3800 | |
| | | Variance | | 0.270 | |
| | | Std. Deviation | | 0.52006 | |
| | | Minimum | | 2.04 | |
| | | Maximum | | 4.08 | |
| | | Range | | 2.04 | |
| | | Interquartile Range | | 0.68 | |
| | | Skewness | | −0.624 | 0.472 |
| | | Kurtosis | | 0.327 | 0.918 |

Table 5. ANOVA test result of pretest and posttest score

| | | Sum of Squares | *df* | Mean Square | *F* | Sig. |
|---|---|---|---|---|---|---|
| Pretest | Between Groups | 0.244 | 1 | 0.244 | 1.142 | 0.291 |
| | Within Groups | 9.811 | 46 | 0.213 | | |
| | Total | 10.055 | 47 | | | |
| Posttest | Between Groups | 4.225 | 1 | 4.225 | 14.969 | 0.000 |
| | Within Groups | 12.982 | 46 | 0.282 | | |
| | Total | 17.206 | 47 | | | |

*df* = Degrees of Freedom; *F* = *F*-Value; Sig. = Significance Value

Our findings that the PjBL-T+AR cohort outperformed the non-PjBL-T+AR cohort with a large, practically meaningful posttest effect—align with international reports that AR improves complex procedural learning, accuracy, and decision quality in industrial/automotive contexts [22, 23, 25, 26], and with studies showing AR's motivational and spatial-reasoning benefits in technical tasks [20, 25, 26]. At the same time, they extend PjBL evidence

that authentic, collaborative projects can bolster higher-order thinking and relevance in engineering education [8, 9]. Taken together, our results support a mechanistic account: AR contributes visualization, safe iterative practice, and just-in-time cues, while PJBL-T contributes structured inquiry via troubleshooting cycles.

## V. Conclusion

The findings of this study indicate that the assumptions for parametric testing were met, as the pretest scores in both the PjBL-T Augmented Reality group and the non-PjBL-T Augmented Reality group were normally distributed ($p > 0.05$) and demonstrated homogeneous variances ($p > 0.05$). The ANOVA results for the pretest ($F = 1.142$, $p = 0.291$) confirmed that there was no significant difference in students' critical thinking skills between the two groups prior to the intervention, showing that both groups began with equivalent abilities. However, the ANOVA results for the posttest ($F = 14.969$, $p = 0.000$) revealed a significant difference in favor of the experimental group. These results suggest that the use of Project-Based Learning with Technology (PjBL-T) integrated with Augmented Reality effectively enhanced students' critical thinking skills compared to instruction without PjBL-T and Augmented Reality. These results align with prior findings on PjBL and HOTS development, technology-supported cognitive skill formation, and troubleshooting-driven diagnostic reasoning in vocational settings, and are consistent with recent reports that AR can enhance conceptual clarity and decision quality in complex mechanical tasks. Within the study's conditions (8-week dosage, matched facilities, fidelity-checked delivery), PjBL-T integrated with AR thus offers a theory-consistent and practically meaningful route to strengthening critical thinking in automotive chassis education. Consequently, the hypothesis of this study is accepted, indicating that PjBL-T with Augmented Reality provides a significant positive impact on students' critical thinking development.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Hanapi Hasan contributed to the conceptualization, research design, and overall supervision of the study. Wakhinuddin Simatupang was responsible for methodology development, validation of instructional design, and critical review of the manuscript. Wawan Purwanto handled data collection, classroom implementation, and technical validation of the PjBL-T model. Hasan Maksum contributed to statistical analysis, interpretation of findings, and ensuring the rigor of data analysis. M. Giatman managed project administration, funding acquisition, and coordination between institutions. Riki Mukhaiyar developed the software, integrated the Augmented Reality simulation, and performed technical troubleshooting. Eko Indrawan conducted the literature review, prepared the theoretical framework, and drafted the methodology section. Wan Ahmad Jaafar Wan Yahaya provided international collaboration, manuscript refinement, and insights on AR-based learning models. Tansa Trisna Astono Putri was responsible for writing the original draft, editing, and visualization of the results; all authors had approved the final version.

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