

Evaluating an augmented reality–integrated project-based learning model for RWD powertrain

Muslim^{1*}, Wagino¹, Iffarial Nanda¹, Rido Putra¹, Lasyatta Syaifullah¹, Hsu-Chan Kuo², Volodymyr Tymofiiv³, and Ivana Koláriková³

¹ Universitas Negeri Padang, Padang, Indonesia

² National Cheng Kung University, Tainan, Taiwan

³ Technical University of Košice, Košice, Slovakia

*Corresponding author's email: muslim@ft.unp.ac.id

Abstract

This study developed, validated, and practicalized an augmented reality-supported project learning model for automotive powertrain instruction, using a rear-wheel drivetrain laboratory scenario as the main AR training medium. The work focused on confirming the model's conceptual soundness, alignment with powertrain learning demands, and feasibility for classroom implementation, especially in workshops with limited equipment access. Model validation results showed very strong expert agreement on structural integrity, along with high reliability in learning component evaluation. Practicality testing demonstrated consistent usability and acceptance from instructors and students, all scoring above the expected feasibility threshold, with the highest ratings observed in learning interaction and adaptability to learner needs. The AR environment strengthened students' ability to interpret internal torque transfer, understand mechanical behavior, and perform component identification more confidently. These findings indicate that AR-mediated project learning can improve interaction quality, mechanism comprehension, and practical reasoning readiness. The model demonstrates strong potential for scalable adoption in automotive engineering programs, with future work expected to explore extended field application and learning optimization.

Keywords

Augmented reality, Project-based learning, Rear-wheel drive, Automotive powertrain technology, Quality education

Introduction

Powertrain education represents a critical domain within automotive engineering, given the escalating complexity of contemporary vehicle architectures and the corresponding demand for graduates who demonstrate rigorous theoretical proficiency and advanced practical competence. As modern automotive technologies increasingly prioritize

Published:
May 04, 2026

This work is licensed under a [Creative Commons Attribution-NonCommercial 4.0 International License](#)

Selection and Peer-review under the responsibility of the 7th BIS-HSS 2025 Committee

efficiency, safety, digital integration, and environmental sustainability, a comprehensive understanding of powertrain configuration, system dynamics, and component-level interactions is required to satisfy evolving industry standards [1]. Recent AR/VR syntheses document the accelerated adoption of immersive technologies in automotive design, technical training, and maintenance operations, thereby reinforcing their instructional relevance for vehicle-system education [2]. Nevertheless, persistent pedagogical constraints remain evident: restricted access to high-cost and risk-intensive laboratory equipment limits sustained hands-on engagement [3], and a substantive disconnect continues to be observed between classroom-based theoretical instruction and industrial practice [4]. Collectively, these conditions substantiate the necessity for pedagogical frameworks capable of systematically integrating conceptual knowledge with authentic, practice-oriented learning experiences.

From a cognitive standpoint, powertrain instruction is frequently impeded by the limited observability of essential mechanical processes, including torque-transfer synchronization, differential motion, and internal transmission dynamics, which cannot be directly visualized during conventional demonstrations. From an infrastructural standpoint, vocational institutions commonly encounter equipment limitations that restrict repetitive disassembly, real-time experimentation, and safe exposure to rotating assemblies. From an industry-alignment standpoint, the rapid integration of digital diagnostics and AR-assisted maintenance systems intensifies expectations that graduates exhibit both mechanistic reasoning and digital-technology fluency. Accordingly, the development of a systematically structured instructional model integrating conceptual visualization, project-based inquiry, and simulation-supported experimentation becomes not merely advantageous but pedagogically imperative.

Recent advances in engineering education underscore the capacity of immersive technologies to mitigate these instructional constraints. Project-Based Learning (PjBL) is extensively recognized for promoting collaborative inquiry, higher-order reasoning, and engagement with authentic engineering problems. When operationalized in conjunction with Augmented Reality (AR), PjBL environments can facilitate interactive visualization and manipulation of complex mechanical subsystems that are otherwise difficult to observe directly [5]. Contemporary AR classifications further delineate its expanding applicability across educational and industrial sectors. Empirical findings consistently indicate that AR-supported learning environments are associated with enhanced learner motivation, engagement, and cognitive activation [6], while AR-enabled computational-thinking scaffolds contribute to the strengthening of structured problem-solving processes in technical domains [7].

Within automotive engineering education, AR-supported PjBL demonstrates considerable potential for simulating intricate powertrain mechanisms, representing dynamic system behavior, and enabling safe as well as cost-efficient exploration of component functionality. Industrial implementations increasingly employ AR for visual inspection, diagnostic guidance, and interaction with occluded mechanical structures

[8]. Existing AR configurations range from mobile marker-based applications to advanced head-up display systems incorporating real-time rendering and eye-tracking functionalities, each characterized by specific trade-offs in terms of stability, latency, and hardware dependency [9]. In the present study, the AR medium visualizes a rear-wheel-drive (RWD) powertrain-comprising the clutch, transmission, driveshaft, differential, and rear axle-within an augmented environment. The geometric fidelity of components and the precision of spatial registration are regarded as essential prerequisites for credible overlays, as emphasized in prior investigations concerning three-dimensional measurement and alignment accuracy [10]. Through AR-mediated simulations, learners are enabled to perform virtual inspection, observe mechanical synchronization, and engage in functional reasoning without exposure to equipment-related hazards. Previous empirical studies suggest that such simulations can enhance experiential learning while concurrently reducing safety risks [11], [12]. The increasing reliance of industrial sectors on AR-assisted manufacturing and maintenance systems further reinforces the importance of curricular alignment with emerging digital-industry practices [13]. In addition, context-aware AR assistance frameworks inform the design of PjBL-AR environments capable of delivering implicit and adaptive guidance during technical task execution [14].

Despite these developments, limited research has systematically integrated PjBL and AR within a unified instructional model explicitly designed for powertrain education. Although AR is frequently associated with the cultivation of Industry 4.0 competencies [15], prior investigations provide insufficient empirical examination of model validity, pedagogical coherence, and classroom-level practicality. Systematic reviews advocate the application of rigorous mixed-method designs-including usability metrics, learning-gain measurements, and qualitative feedback analyses-when evaluating AR-enhanced instructional interventions [16]. Concurrently, trends in mobile learning indicate a progressive transition toward interactive and personalized ecosystems, thereby supporting the implementation of mobile-based AR within technical education contexts [17], [18]. These converging insights collectively highlight the need for structured empirical inquiry addressing both the theoretical robustness and the operational feasibility of integrated AR-PjBL frameworks.

Accordingly, the principal problem addressed in this investigation concerns the absence of a validated and pedagogically coherent AR-integrated Project-Based Learning model specifically formulated for rear-wheel-drive (RWD) powertrain instruction in vocational automotive education. Existing studies predominantly emphasize either AR media development without systematic validation of the associated instructional architecture, or PjBL implementation without immersive visualization tailored to complex mechanical subsystems. Such fragmentation constrains theoretical integration, empirical rigor, and instructional transferability.

To respond to this identified gap, the present study develops, validates, and evaluates an AR-supported PjBL model designed for powertrain instruction, with the

rear-wheel-drive (RWD) system functioning as the central AR medium. The investigation is aligned with contemporary calls for virtual-prototyping-oriented engineering education, wherein AR/VR systems are expected to accelerate conceptual acquisition and reduce barriers to technical exploration [19]. The contribution of this study resides in its integrated technical-pedagogical architecture, which systematically incorporates: (1) a structured PjBL syntax aligned with mechanistic reasoning in powertrain systems; (2) a mobile marker-based AR visualization adaptable to resource-constrained laboratory environments; and (3) a multi-stage evaluation framework encompassing expert validation, practicality assessment, and empirical analysis of student learning outcomes. In contrast to prior research that primarily evaluates AR applications in terms of usability or motivational impact, the present study concurrently examines theoretical soundness, instructional coherence, and implementation feasibility within authentic classroom. The scope of the investigation includes model development, expert appraisal, classroom implementation, and measurement of its effects on interaction quality, conceptual comprehension, and practical competence, thereby ensuring alignment between research objectives and empirical inferences.

Method

This investigation adopted a Research and Development (R&D) methodology structured in accordance with the Four-D model-Define, Design, Develop, and Disseminate-which is extensively recognized as a systematic framework for the development, validation, and refinement of instructional products [20]. During the Define phase, a comprehensive needs analysis was undertaken, incorporating literature synthesis, curriculum mapping, and learner-profile diagnostics to identify recurrent conceptual and procedural constraints encountered in automotive powertrain instruction, particularly within rear-wheel-drive (RWD) system configurations. Empirical evidence emphasizing the pedagogical value of immersive and authentic engineering learning environments [3], [4] provided the theoretical justification for integrating Augmented Reality (AR) media designed to visualize RWD component structures, kinematic relationships, and mechanical interactions.

In the Design phase, a prototype instructional architecture was formulated, comprising: (1) learning scenarios aligned with the AR-supported Project-Based Learning (PjBL) syntax; (2) RWD powertrain AR visualization modules; and (3) competency-based assessment instruments calibrated to learning indicators. The AR modules enabled visualization of principal mechanical subsystems-namely the clutch assembly, transmission unit, propeller shaft, differential mechanism, and final drive-thereby supporting conceptual internalization through dynamic and spatially coherent representations. The technical development process followed a structured digital production pipeline, encompassing three-dimensional (3D) modeling, AR system integration, interface configuration, and Android-based deployment. The sequential workflow of this development process is presented in Figure 1.

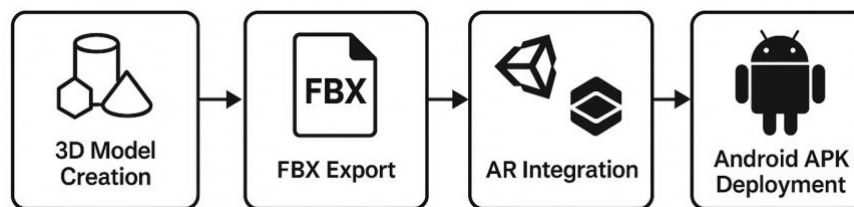


Figure 1. AR development workflow

Source: self-constructed by the authors using public-domain workflow icon conventions from OpenClipart, Wikimedia Commons (FBX icon), and Unity interface symbol style

The Develop phase incorporated expert validation procedures, iterative prototype refinement, and limited-scale classroom pilot implementation. A panel of fifteen experts in instructional technology and automotive powertrain systems evaluated construct validity and content validity employing Aiken's V coefficients as the principal quantitative indicator. Subsequently, practicality testing was conducted with five lecturers and thirty automotive engineering students, who assessed usability, clarity, instructional feasibility, and operational effectiveness through structured questionnaire instruments with percentage-based scoring.

In the Disseminate phase, the validated AR-supported PjBL model and corresponding RWD AR media were formally documented and disseminated to academic and professional stakeholders. This stage was intended to facilitate broader adoption, strengthen alignment with Industry 4.0 competency frameworks, and support systematic integration of AR-enhanced instructional models within vocational powertrain education contexts.

Results

The implementation of the Augmented Reality-supported Project-Based Learning (AR-supported PjBL) model, employing AR media specifically developed for the rear-wheel-drive (RWD) powertrain system, generated comprehensive empirical evidence encompassing construct validity, content validity, and practicality evaluation. These findings collectively demonstrate that the model exhibits substantial structural coherence, curricular alignment, and pedagogical feasibility within authentic vocational instructional contexts. All empirical data were systematically collected from subject-matter experts, lecturers, and students in accordance with the predefined research protocol and quantitative validation procedures.

Construct validity of the AR-supported PjBL model

Construct validity was evaluated through expert judgment utilizing Aiken's V coefficients, outer loading values, composite reliability indices, Average Variance Extracted (AVE), and discriminant validity measures. As presented in Table 1, all five principal constructs—Model Syntax, Social System, Reaction Principles, Instructional Impact, and Accompanying Impact—demonstrated high levels of statistical adequacy. Aiken's V coefficients ranged from 0.93 to 0.97, with the Social System and Instructional

Impact dimensions attaining the highest value (0.97), indicating very strong expert agreement regarding construct representativeness and conceptual clarity.

Furthermore, all outer loading coefficients exceeded the 0.90 threshold, signifying strong indicator reliability. Composite reliability values were consistently above 0.95, confirming robust internal consistency across measurement items. AVE values greater than 0.80 indicate that each construct accounted for more than 80% of the variance in its respective indicators, thereby supporting convergent validity. Discriminant validity values also remained within acceptable parameters, confirming adequate construct differentiation. Collectively, these quantitative indicators substantiate the theoretical soundness and measurement robustness of the AR-supported PjBL model.

Table 1. Construct validity of the AR-supported PjBL model (Aiken's V)

Construct Validation	Σs	Aiken's V	Outer Loading	Composite Reliability	AVE	Discriminant Validity
Model Syntax	57	0.95	0.915	0.957	0.837	0.915
Social System	58	0.97	0.933	0.965	0.871	0.933
Reaction Principles	56	0.93	0.908	0.952	0.824	0.908
Instructional Impact	58	0.97	0.933	0.965	0.871	0.933
Accompanying Impact	57	0.95	0.925	0.961	0.856	0.925

Content validity and curricular alignment

Content validity analysis further confirmed strong alignment between the structural components of the model and the curricular requirements of automotive powertrain instruction. As summarized in Table 2, six evaluated dimensions-AR Integration, Project Design, Collaboration and Communication, Problem Solving, Assessment and Reflection, and Material Relevance-achieved Aiken's V coefficients ranging from 0.85 to 0.91. These values indicate high levels of expert agreement regarding indicator relevance and clarity.

The problem-solving dimension obtained the highest coefficient (0.91), suggesting that the model is perceived as highly effective in fostering analytical reasoning, torque-flow interpretation, and troubleshooting competence within RWD powertrain. Composite reliability values ranged between 0.89 and 0.93, demonstrating satisfactory internal consistency, while AVE values exceeding 0.70 confirm adequate convergent validity. Discriminant validity indices also remained within acceptable limits, supporting construct distinctiveness. Overall, the content validation results indicate that the AR-supported PjBL model is pedagogically aligned with competency-based automotive curricula.

Table 2. Content validity of the AR-supported PjBL model (Aiken's V)

Construct Validation	Σs	Aiken's V	Outer Loading	Composite Reliability	AVE	Discriminant Validity
Integration AR	60	0.89	0.85	0.92	0.76	0.87
Project Design	58	0.86	0.82	0.90	0.73	0.85
Collaboration and Communication	59	0.88	0.84	0.91	0.75	0.86
Problem Solving	61	0.91	0.87	0.93	0.78	0.88

Construct Validation	Σs	Aiken's V	Outer Loading	Composite Reliability	AVE	Discriminant Validity
Assessment and Reflection	57	0.85	0.81	0.89	0.72	0.84
Material Relevance	59	0.88	0.84	0.91	0.75	0.86

Practicality and implementation feasibility

Practicality evaluation was conducted to determine the usability, operational feasibility, and instructional effectiveness of the model within authentic classroom settings. The assessment involved lecturers and students who provided structured responses based on percentage-based scoring criteria. As indicated in Table 3, all evaluated aspects exceeded the 80% practicality threshold, thereby satisfying the predefined acceptance criterion for instructional deployment.

The Interaction in Learning aspect achieved the highest percentage scores (85.60% from lecturers and 85.20% from students), indicating that the RWD AR media substantially supported collaborative engagement, communicative interaction, and coordinated problem-solving activities. Suitability to Learning Style also demonstrated consistently high ratings (84.00% across both respondent groups), suggesting adaptability to diverse learner preferences through interactive visualization and spatial representation. Notably, even the lowest-rated dimension-Learning Atmosphere-remained within the high-practicality category (80.80%–81.20%), indicating overall positive instructional reception.

Table 3. Practicality assessment of the AR-supported PjBL model

Assessment Aspect	Lecturer Practicality			Student Practicality		
	Total Score	Maksimum Score	% Practicality	Total Score	Maksimum Score	% Practicality
Attraction Aspect	104	125	83.20%	621	750	82.80%
Ease of Implementation Aspect	104	125	83.20%	627	750	83.60%
Aspects of Learning Atmosphere	101	125	80.80%	609	750	81.20%
Interaction Aspects in Learning	107	125	85.60%	639	750	85.20%
Time Efficiency	102	125	81.60%	613	750	81.73%
Flexibility and Sustainability	103	125	82.40%	617	750	82.27%
Ease of Evaluation	104	125	83.20%	624	750	83.20%
Suitability to Learning Style	105	125	84.00%	630	750	84.00%

To further demonstrate the functional performance of the AR system, Figure 2 illustrates the marker employed within the RWD module and the corresponding three-dimensional overlay generated during real-time visualization. This visual evidence supports the technical feasibility of the AR implementation and its alignment with the validated instructional architecture.

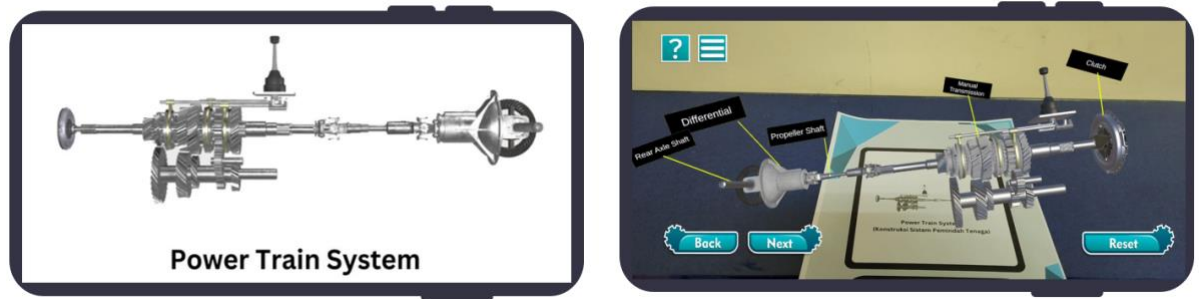


Figure 2. AR marker (left) and the resulting AR overlay (right)
Source: Own elaboration

Discussion

The findings of this investigation indicate that the Augmented Reality-supported Project-Based Learning (AR-supported PjBL) model provides significant pedagogical contributions to powertrain instruction, particularly in enhancing conceptual comprehension of rear-wheel-drive (RWD) system architecture and functional dynamics. When interpreted in relation to the quantitative validation indices and practicality percentages reported in the Results section, the model demonstrates not only empirical adequacy but also theoretical coherence within vocational automotive education.

Construct validity and theoretical grounding of the AR-supported PjBL model

The high construct validity coefficients—most notably Aiken’s V values of 0.95 for Model Syntax and 0.97 for Social System—indicate strong expert agreement regarding the representativeness and structural integrity of the instructional framework. These statistical indicators, supported by outer loading values exceeding 0.90, composite reliability coefficients above 0.95, and AVE scores greater than 0.80, confirm measurement robustness and internal consistency across constructs. Such quantitative strength substantiates the theoretical grounding of the AR-supported PjBL architecture.

From a pedagogical perspective, the validated Model Syntax dimension reflects the systematic sequencing of inquiry phases characteristic of PjBL, including problem identification, investigation, collaborative analysis, and reflective synthesis. The Social System construct, which attained the highest Aiken’s V value (0.97), corresponds to structured interaction patterns that facilitate coordinated reasoning and distributed cognition during mechanical exploration. These findings are consistent with evidence that AR technologies transform abstract mechanical phenomena into manipulable, spatially coherent representations capable of enhancing cognitive processing efficiency [21]. Furthermore, prior research on AR interaction design within industrial and assembly environments demonstrates that intuitive visual overlays can improve comprehension accuracy and collaborative coordination [22]. Consequently, the empirical strength of the construct indicators may be interpreted as reflecting both statistical validity and pedagogical legitimacy.

The observed instructional improvements can also be attributed to the synergistic integration of AR visualization and Project-Based Learning methodology. PjBL is widely acknowledged for fostering inquiry-based engagement, shared problem-solving, and higher-order reasoning processes [23], [24], while AR enables dynamic representation of torque distribution, gear sequencing, and differential motion within visually constrained systems. This integration supports the transition from abstract conceptualization to concrete mental modeling, as emphasized in prior AR-based engineering studies [25], and parallels AR-assisted assembly frameworks in which spatial precision contributes to enhanced decision-making accuracy and procedural alignment [26]. Together, these elements form a coherent instructional ecosystem.

Content validity and enhancement of problem-solving competence

The content validation results, particularly the Aiken's V coefficient of 0.91 for the Problem-Solving dimension, indicate strong expert consensus regarding the relevance and clarity of analytical reasoning indicators embedded within the model. This quantitative evidence corresponds with observed improvements in students' diagnostic reasoning, hypothesis formulation, and comparative scenario evaluation during AR-mediated simulations. The ability to analyze torque-flow pathways, evaluate mechanical synchronization, and validate interpretative assumptions reflects the operationalization of higher-order cognitive processes.

These findings align with prior investigations demonstrating that AR-supported environments can facilitate iterative experimentation, scenario-based comparison, and structured reasoning cycles. In particular, the AR simulations implemented in this study resemble procedural AR training models in which stepwise visual cues and controlled scenario variation strengthen analytical refinement and technical judgment [27]. Thus, the elevated content validity coefficients are not merely statistical artifacts but may be interpreted as indicators of functional alignment between instructional design and targeted competency development.

Practicality, procedural readiness, and cognitive support

The consistently high practicality percentages—84.00% for Suitability to Learning Style and 83.00% for Ease of Implementation—demonstrate that the AR-supported PjBL model is operationally feasible within authentic classroom and laboratory environments. These values exceed the predefined 80% acceptance threshold, thereby confirming instructional deploy ability. Beyond feasibility, the practicality data suggest that AR-based pre-practice visualization can enhance procedural readiness prior to hands-on mechanical engagement.

Such outcomes are consistent with embodied learning perspectives, which posit that cognitive understanding is strengthened through multimodal interaction with spatial representations. Empirical evidence from AR-assisted assembly research similarly reports improvements in task accuracy and reductions in operational errors when visual guidance is integrated into procedural instruction [28]. Moreover, the reported

reduction in cognitive strain during practical activities parallels findings from AR-supported automotive assembly environments, where ergonomic visualization contributes to decreased fatigue and improved task performance efficiency [29]. These converging findings suggest that AR integration may optimize both cognitive and procedural dimensions of powertrain learning.

Interaction, motivation, and collaborative engagement

The highest practicality ratings were observed in the Interaction in Learning dimension (85.60% from lecturers and 85.20% from students), indicating strong perceived effectiveness in fostering collaborative discourse and communicative engagement. Such elevated percentages suggest that the AR-supported PjBL framework facilitates social negotiation of meaning during mechanical investigation tasks.

These results are consistent with research demonstrating that AR-based learning environments can enhance emotional involvement, sustained attention, and participatory persistence [30]. In vocational and automotive education contexts, perceived usefulness and interactive affordances have been shown to significantly influence learner satisfaction and technology acceptance [31]. Accordingly, the interaction-related practicality scores may reflect both motivational enhancement and perceived instructional value.

Blended learning reinforcement and distributed cognitive presence

The blended-learning implementation strategy, which enabled access to AR materials both within and beyond the classroom setting, appears to have reinforced distributed cognitive engagement. Such flexibility aligns with blended-learning frameworks that emphasize sustained interaction across temporal and spatial boundaries [32]. The readiness observed during in-person practical sessions suggests that off-site rehearsal through AR visualization may contribute to improved performance confidence and task accuracy.

Comparable outcomes have been reported in AR-mediated medical and vocational training contexts, where preliminary simulation exposure enhances precision and procedural stability during subsequent physical execution [33]. Therefore, the blended integration of AR-supported PjBL may function as a mechanism for extending cognitive presence beyond conventional classroom constraints.

Technical constraints and usability considerations

Notwithstanding the positive empirical indicators, several technical constraints were identified during implementation. Tracking instability and device heterogeneity correspond to widely documented usability challenges in AR research [34]. Marker-based mobile deployments are particularly sensitive to calibration accuracy, lighting stability, and marker configuration parameters, as reported in previous technical analyses [35], [36].

Additionally, variations in student digital literacy levels may influence interaction fluency and cognitive load. Prior vocational AR studies emphasize the necessity of structured onboarding procedures and scaffolded interface design to support user readiness and reduce extraneous cognitive burden [37]. Addressing these constraints through adaptive interface optimization, standardized device provisioning, and exploration of markerless tracking technologies may enhance instructional reliability and scalability in future iterations.

Broader implications and future research directions

Collectively, the discussion reinforces an expanding body of literature indicating that AR-supported PjBL can enhance conceptual understanding, procedural competence, and affective engagement within technical education domains. The RWD AR media developed in this study contribute to bridging the persistent gap between theoretical exposition and practical skill acquisition, consistent with contemporary innovations in digital-twin integration and Industry 4.0-aligned instructional ecosystems [38], [39].

Future investigations are expected to benefit from longitudinal research designs capable of examining retention stability, transferability of diagnostic reasoning, and sustained motivational impact. The integration of adaptive learning analytics, as recommended in recent AR industry reviews [40], may enable personalization of learning pathways and real-time performance feedback. Moreover, expansion toward human-robot collaborative learning environments and the incorporation of IoT-driven or AI-supported feedback mechanisms [41], [42] may further strengthen ecological validity, workforce alignment, and technological sustainability.

Conclusion

This study demonstrates that the Augmented Reality-supported Project-Based Learning (AR-supported PjBL) model, operationalized through Rear-Wheel Drive (RWD) AR media, exhibits strong theoretical coherence, high empirical validity, and substantial instructional feasibility within automotive powertrain education. Construct validation results, derived from expert judgment, yielded Aiken's V coefficients ranging from 0.93 to 0.97 across five principal dimensions-Model Syntax, Social System, Reaction Principles, Instructional Impact, and Accompanying Impact-supported by outer loading values exceeding 0.90, composite reliability coefficients above 0.95, and AVE scores greater than 0.80. These quantitative indicators confirm internal consistency, conceptual adequacy, and structural alignment of the developed instructional model.

Content validation further affirmed curricular relevance, with Aiken's V values between 0.85 and 0.91 across six instructional dimensions. The Problem-Solving construct achieved the highest coefficient (0.91), indicating strong expert agreement regarding its effectiveness in supporting analytical reasoning, torque-flow interpretation, and diagnostic decision-making within visually constrained RWD instructional.

Practicality evaluation results demonstrated that all assessed aspects surpassed the 80% acceptance criterion among both lecturers and students. Interaction in Learning achieved the highest percentages (85.60% and 85.20%, respectively), while Suitability to Learning Style maintained consistent ratings of 84.00% across respondent groups. These findings indicate that the AR-supported PjBL model is not only theoretically validated and empirically supported but also instructionally deployable under resource-constrained laboratory conditions.

References

1. J. Park, S. Choi, J. Oh, and J. Eo, 'Adaptive slip engagement control of a wet clutch in vehicle powertrain based on transmitted torque estimation', *Mechanical Systems and Signal Processing*, vol. 171, p. 108861, May 2022, doi: 10.1016/j.ymsp.2022.108861.
2. Z. Čujan, G. Fedorko, and N. Mikušová, 'Application of virtual and augmented reality in automotive', *Open Engineering*, vol. 10, no. 1, pp. 113–119, Jan. 2020, doi: 10.1515/eng-2020-0022.
3. M. Hernandez-de-Menendez, A. V. Guevara, J. C. T. Martinez, D. H. Alcantara, and R. Morales-Menendez, 'Active learning in engineering education. A review of fundamentals, best practices and experiences', *International Journal on Interactive Design and Manufacturing (ijidem)*, vol. 13, no. 3, pp. 909–922, Sept. 2019, doi: 10.1007/S12008-019-00557-8.
4. S. R. Brunhaver, R. F. Korte, S. R. Barley, and S. D. Sheppard, 'Bridging the Gaps between Engineering Education and Practice', in *U.S. Engineering in a Global Economy*, R. B. Freeman and H. Salzman, Eds, University of Chicago Press, 2018, p. 0. doi: 10.7208/chicago/9780226468471.003.0005.
5. M. Muslim, A. Ambiyar, A. K. Karudin, M. S. H. Ruslan, H.-C. Kuo, and D. T. P. Yanto, 'Project-based Augmented Reality (PjBAR): Evaluation for Vocational Education Effectiveness', *Data and Metadata*, vol. 3, p. .661-.661, Dec. 2024, doi: 10.56294/dm2024.661.
6. M. Mailizar and R. Johar, 'Examining Students' Intention to Use Augmented Reality in a Project-Based Geometry Learning Environment', *INT J INSTRUCTION*, vol. 14, no. 2, pp. 773–790, Apr. 2021, doi: 10.29333/iji.2021.14243a.
7. M. F. A. Hanid, M. N. H. M. Said, N. Yahaya, and Z. Abdullah, 'The Elements of Computational Thinking in Learning Geometry by Using Augmented Reality Application', *International Journal of Interactive Mobile Technologies (IJIM)*, vol. 16, no. 02, pp. 28–41, Jan. 2022, doi: 10.3991/ijim.v16i02.27295.
8. A. Chouchene, A. Ventura Carvalho, F. Charrua-Santos, and W. Barhoumi, 'Augmented Reality-Based Framework Supporting Visual Inspection for Automotive Industry', *Applied System Innovation*, vol. 5, no. 3, p. 48, June 2022, doi: 10.3390/asi5030048.
9. J. Lee et al., 'Automotive augmented reality 3D head-up display based on light-field rendering with eye-tracking', *Opt. Express, OE*, vol. 28, no. 20, pp. 29788–29804, Sept. 2020, doi: 10.1364/OE.404318.
10. X. Liu, Z. Zhang, N. Gao, and Z. Meng, '3D shape measurement of diffused/specular surface by combining fringe projection and direct phase measuring deflectometry', *Opt. Express, OE*, vol. 28, no. 19, pp. 27561–27574, Sept. 2020, doi: 10.1364/OE.402432.
11. C. B. D. Lima, S. Walton, and T. Owen, 'A critical outlook at augmented reality and its adoption in education', *Computers and Education Open*, vol. 3, p. 100103, Dec. 2022, doi: 10.1016/j.caeo.2022.100103.
12. M. Živičnjak, M. Mikulčić, T. Rožić, and B. Rigo, 'Application of container terminal virtual reality in student education', *Transportation Research Procedia*, vol. 74, pp. 26–33, Jan. 2023, doi: 10.1016/j.trpro.2023.11.108.
13. D. Gonzalez-Argote, A. A. Vitón-Castillo, and J. Gonzalez-Argote, 'Application of augmented reality in automotive industry', *EAI Endorsed Transactions on Internet of Things*, vol. 10, Feb. 2024, doi: 10.4108/eetiot.5223.
14. E. Lampen, J. Lehwald, and T. Pfeiffer, 'A Context-Aware Assistance Framework for Implicit Interaction with an Augmented Human', in *Virtual, Augmented and Mixed Reality. Industrial and Everyday Life Applications*, J. Y. C. Chen and G. Fragomeni, Eds, Cham: Springer International Publishing, 2020, pp. 91–110. doi: 10.1007/978-3-030-49698-2_7.
15. S. Machała, N. Chamier-Gliszczyński, and T. Królikowski, 'Application of AR/VR Technology in Industry 4.0.', *Procedia Computer Science*, vol. 207, pp. 2990–2998, Jan. 2022, doi: 10.1016/j.procs.2022.09.357.
16. K. Mukhtarkyzy, G. Abildinova, M. Serik, K. Kariyeva, and O. Sayakov, 'Systematic Review of

- Augmented Reality Methodologies for High School Courses', *International Journal of Engineering Pedagogy (IJEP)*, vol. 13, no. 4, pp. 79–92, June 2023, doi: 10.3991/ijep.v13i4.38165.
17. Y. Singh and P. K. Suri, 'A Bibliometric Analysis of the Literature on Mobile Learning Adoption and Continuance in the Field of Education', *International Journal of Interactive Mobile Technologies (IJIM)*, vol. 17, no. 17, pp. 38–58, Sept. 2023, doi: 10.3991/ijim.v17i17.40965.
 18. L. Xu, M. N. A. Rahman, S. Y. Wong, and Z. Chen, 'Personalized and Interactive Mobile Learning in Early Childhood Education: A Bibliometric Study (2015–2024)', *International Journal of Interactive Mobile Technologies (IJIM)*, vol. 19, no. 10, pp. 86–111, May 2025, doi: 10.3991/ijim.v19i10.53587.
 19. L. Frizziero, L. Galletti, L. Magnani, E. G. Meazza, and M. Freddi, 'Blitz Vision: Development of a New Full-Electric Sports Sedan Using QFD, SDE and Virtual Prototyping', *Inventions*, vol. 7, no. 2, p. 41, June 2022, doi: 10.3390/inventions7020041.
 20. S. Thiagarajan and A. Others, 'Instructional development for training teachers of exceptional children: a sourcebook', Council for Exceptional Children, 1920 Association Drive, Reston, Virginia 22091 (Single Copy, \$5, 1974. Accessed: Jan. 19, 2023. [Online]. Available: <https://eric.ed.gov/?id=ED090725>
 21. A. Palacios-Ibáñez, R. Navarro-Martínez, J. Blasco-Esteban, M. Contero, and J. D. Camba, 'On the application of extended reality technologies for the evaluation of product characteristics during the initial stages of the product development process', *Computers in Industry*, vol. 144, p. 103780, Jan. 2023, doi: 10.1016/j.compind.2022.103780.
 22. S. Aivaliotis et al., 'An augmented reality software suite enabling seamless human robot interaction', *International Journal of Computer Integrated Manufacturing*, Jan. 2023, Accessed: Sept. 24, 2025. [Online]. Available: <https://www.tandfonline.com/doi/abs/10.1080/0951192X.2022.2104459>
 23. D. Kokotsaki, V. Menzies, and A. Wiggins, 'Project-based learning: A review of the literature', *Improving Schools*, vol. 19, no. 3, pp. 267–277, Nov. 2016, doi: 10.1177/1365480216659733.
 24. J. Thomas, *A Review of Research on Project-Based Learning*. San Rafael: CA: Autodesk Foundation, 2000.
 25. N. Abdullah, V. L. Baskaran, Z. Mustafa, S. R. Ali, and S. H. Zaini, 'Augmented Reality: The Effect in Students' Achievement, Satisfaction and Interest in Science Education', *International Journal of Learning, Teaching and Educational Research*, vol. 21, no. 5, Art. no. 5, June 2022, Accessed: Oct. 04, 2024. [Online]. Available: <https://www.ijlter.org/index.php/ijlter/article/view/5292>
 26. S. Aivaliotis et al., 'An interactive Augmented Reality based framework assisting operators in human-robot collaborative assembly operations', *Procedia CIRP*, vol. 126, pp. 170–175, Jan. 2024, doi: 10.1016/j.procir.2024.08.319.
 27. K. Lotsaris et al., 'Augmented Reality (AR) based framework for supporting human workers in flexible manufacturing', *Procedia CIRP*, vol. 96, pp. 301–306, Jan. 2021, doi: 10.1016/j.procir.2021.01.091.
 28. M. D. Mura and G. Dini, 'A proposal of an assembly workstation for car panel fitting aided by an augmented reality device', *Procedia CIRP*, vol. 103, pp. 225–230, Jan. 2021, doi: 10.1016/j.procir.2021.10.036.
 29. W. Mao, X. Yang, C. Wang, Y. Hu, and T. Gao, 'A Physical Fatigue Evaluation Method for Automotive Manual Assembly: An Experiment of Cerebral Oxygenation with ARE Platform', *Sensors*, vol. 23, no. 23, p. 9410, Jan. 2023, doi: 10.3390/s23239410.
 30. C. E. Mendoza-Ramírez, J. C. Tudon-Martínez, L. C. Félix-Herrán, J. de J. Lozoya-Santos, and A. Vargas-Martínez, 'Augmented Reality: Survey', *Applied Sciences*, vol. 13, no. 18, p. 10491, Jan. 2023, doi: 10.3390/app131810491.
 31. T. Xia, X. Lin, Y. Sun, and T. Liu, 'An Empirical Study of the Factors Influencing Users' Intention to Use Automotive AR-HUD', *Sustainability*, vol. 15, no. 6, p. 5028, Jan. 2023, doi: 10.3390/su15065028.
 32. C. Noll, U. Vo. J. D. R. Biol Hum, and U. R. Med, 'Mobile Augmented Reality as a Feature for Self-Oriented, Blended Learning in Medicine: Randomized Controlled Trial', *JMIR mHealth and uHealth*, vol. 5, no. 9, Sept. 2017, doi: 10.2196/mhealth.7943.
 33. P. Dhar, T. Rocks, R. M. Samarasinghe, G. Stephenson, and C. Smith, 'Augmented reality in medical education: students' experiences and learning outcomes', *Medical Education Online*, Jan. 2021, Accessed: Sept. 24, 2025. [Online]. Available: <https://www.tandfonline.com/doi/abs/10.1080/10872981.2021.1953953>
 34. M. Akçayır and G. Akçayır, 'Advantages and challenges associated with augmented reality for education: A systematic review of the literature', *Educational Research Review*, vol. 20, pp. 1–11, Feb. 2017, doi: 10.1016/j.edurev.2016.11.002.
 35. A. R. Adenan, M. Kassim, and N. A. Kamaluddin, 'The Design of Mobile 3D Augmented Reality on

- Marker Visual Inspection Mask', *International Journal of Interactive Mobile Technologies (IJIM)*, vol. 16, no. 21, Art. no. 21, Nov. 2022, doi: 10.3991/ijim.v16i21.33843.
36. M. Zaifri, H. Khalloufi, F. Z. Kaghat, A. Benlahbib, A. Azough, and K. A. Zidani, 'Enhancing Tourist Experiences in Crowded Destinations through Mobile Augmented Reality: A Comparative Field Study', *International Journal of Interactive Mobile Technologies (IJIM)*, vol. 17, no. 20, pp. 92–113, Nov. 2023, doi: 10.3991/ijim.v17i20.42273.
 37. D. T. P. Yanto, Ganefri, Sukardi, J. P. Yanto, R. Kurani, and Muslim, 'Engineering Students' Acceptance of Augmented Reality Technology Integrated with E-Worksheet in The Laboratory Learning', *International Journal of Online and Biomedical Engineering (IJOE)*, vol. 20, no. 03, Art. no. 03, Feb. 2024, doi: 10.3991/ijoe.v20i03.46101.
 38. R. Efendi, Ambiyar, Estuhono, and R. A. Wulandari, 'Bridging the Industry 4.0 Skills Gap: An Immersive Augmented Reality Mobile Learning Approach for Vocational Education', *International Journal of Interactive Mobile Technologies (IJIM)*, vol. 19, no. 06, pp. 60–74, Mar. 2025, doi: 10.3991/ijim.v19i06.53825.
 39. D. Novaliendry, R. F. Y. Saputra, N. Febrianti, D. T. P. Yanto, F. M. Saragih, and W. M. Y. Rahiman, 'Development of a Digital Twin Prototype for Industrial Manufacturing Monitoring System Using IoT and Augmented Reality', *International Journal of Online and Biomedical Engineering (IJOE)*, vol. 20, no. 03, pp. 4–23, Feb. 2024, doi: 10.3991/ijoe.v20i03.47101.
 40. J. A. Fernández-Moyano, I. Remolar, and Á. Gómez-Cambronero, 'Augmented Reality's Impact in Industry—A Scoping Review', *Applied Sciences*, vol. 15, no. 5, p. 2415, Jan. 2025, doi: 10.3390/app15052415.
 41. M. Cabanillas-Carbonell and J. Zapata-Paulini, 'Improving the Accuracy of Oncology Diagnosis: A Machine Learning-Based Approach to Cancer Prediction', *International Journal of Online and Biomedical Engineering (IJOE)*, vol. 20, no. 11, pp. 102–122, Aug. 2024, doi: 10.3991/ijoe.v20i11.49139.
 42. C. Nataraj, L. W. M. Wei, M. Alagirisamy, and S. K. Selvaperumal, 'Design Of Intelligent Road Eye Using AI And Machine Learning For Automobiles', *EAI Endorsed Transactions on Internet of Things*, vol. 11, Jan. 2025, doi: 10.4108/eetiot.7638.