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CLOSING COMPETENCY GAPS THROUGH PROBLEM-BASED LEARNING IN AUTOMOTIVE VOCATIONAL EDUCATION: PRE-POST EVIDENCE FROM CHASSIS MANAGEMENT SYSTEM TRAINING

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ABSTRAK

Pendidikan vokasi otomotif menuntut peserta didik mentransfer pengetahuan teknis ke keputusan diagnosis dan servis. Penelitian ini menganalisis perubahan kompetensi sistem rem Chassis Management System setelah pembelajaran berbasis Problem-Based Learning (PBL) serta menilai apakah peningkatan disertai konvergensi menuju penguasaan tinggi. Data berpasangan pre-test dan post-test dari 34 siswa kelas XI Ototronik dianalisis menggunakan statistik deskriptif, uji t berpasangan, analisis sensitivitas Wilcoxon, interval kepercayaan, Cohen's dz, normalized gain, ambang penguasaan, dan hubungan skor awal-gain. Rerata meningkat dari 52.35 ± 13.27 menjadi 92.65 ± 7.10 dengan gain 40.29 poin (95% CI 36.22-44.37), $t(33)=20.13$, $p<0.001$, $dz=3.45$. Seluruh siswa meningkat, 79.4% mencapai normalized gain tinggi, dan 97.1% mencapai skor minimal 80. Dispersi post-test menurun. Hasil menunjukkan pola peningkatan universal dan konvergensi kompetensi ke atas, namun desain terkontrol masih diperlukan untuk inferensi kausal.

Kata Kunci: *Problem-Based Learning; automotive vocational education; Chassis Management System; brake-system competence; competence convergence*

ABSTRACT

Automotive vocational education requires learners to transfer technical knowledge into diagnostic and service decisions. This study examined changes in Chassis Management System brake-system competence after Problem-Based Learning (PBL)-supported instruction and whether gains converged toward high mastery. Complete paired pre-test and post-test scores from 34 Grade XI Ototronik students were analyzed using descriptive statistics, paired t testing, Wilcoxon sensitivity analysis, confidence intervals, Cohen's dz, normalized gain, mastery thresholds, and baseline-gain associations. Mean scores increased from 52.35 ± 13.27 to 92.65 ± 7.10, yielding a 40.29-point gain (95% CI 36.22-44.37), t(33)=20.13, p<0.001, dz=3.45. All students improved, 79.4% achieved high normalized gain, and 97.1% scored at least 80. Post-test dispersion decreased. PBL-supported instruction therefore coincided with large, universal gains and an upward competence-convergence pattern, although controlled studies are required for causal inference.
Keywords: *Problem-Based Learning; automotive vocational education; Chassis Management System; brake-system competence; competence convergence*

INTRODUCTION

Vocational education is evaluated by its capacity to prepare learners to use knowledge in occupationally meaningful situations, not merely to reproduce technical information. This theory–practice problem is recurrent across technical and vocational education and training (TVET): classroom instruction can remain strongly theory driven and teacher centered even when employability requires application, judgment, and adaptable problem solving (Schneider et al., 2023). Qualitative evidence from TVET stakeholders likewise frames Problem-Based Learning (PBL) as a way to integrate theory with practice, strengthen self-efficacy, and support graduate competence and employability (Okolie et al., 2021). Adjacent experiential and challenge-oriented models emphasize the same transition from abstract content to authentic work tasks, whether through design-build-test projects, work-integrated learning, or collaborative challenge-based learning (Ali et al., 2025; Rose, 2026; Williams, 2025). For automotive vocational education, this requirement is especially consequential because technical competence involves interpreting system behavior, diagnosing faults, selecting inspection logic, and justifying safe corrective action. A student who can name brake-system components but cannot reason through symptoms and probable causes has not yet demonstrated occupationally usable competence.

Problem-Based Learning is pedagogically relevant to this challenge because it organizes learning around a problem that creates a need to identify prior knowledge, seek new information, compare explanations, and defend a solution. Studies in technical education have reported that PBL can increase engagement and encourage learners to apply prerequisite knowledge rather than remain passive recipients of teacher explanation (Dabir et al., 2022). In vocational settings, teachers and learners also associate problem-based and other practice-centered strategies with hands-on work, collaboration, self-directed exploration, and mastery of practical tasks (Bascuguin & Generoso, 2026; Okolie et al., 2023). Active-learning research in vocational chemistry similarly emphasizes problem-based learning, simulation, and collaborative work as strategies for higher-order thinking and application (Qi et al., 2024), while a quasi-experimental vocational study found that PBL and inquiry-oriented instruction can produce different learning outcomes from conventional approaches (Rafiq et al., 2023). These findings make a problem-centered pedagogy theoretically compatible with Chassis Management System (CMS) learning, where component knowledge must be connected to system-level reasoning.

The literature supplied for this manuscript uses the abbreviation PBL for two related but distinct pedagogies: Problem-Based Learning and Project-Based Learning. This article uses PBL exclusively for Problem-Based Learning. Evidence on Project-Based Learning is treated as adjacent vocational pedagogy rather than as direct evidence for the same intervention. That distinction matters because the project-based literature is substantial and increasingly visible in vocational and STEM education (Ibrahim, 2025), but implementation designs vary widely across applied-science contexts (Sidik et al., 2026). Vocational-school studies describe project-based approaches as supporting labor competences, autonomy, interdisciplinary work, and student-centered practice, while also depending on collaboration, leadership, resources, and professional development (Figueroa et al., 2023; González et al., 2026). Research in the German dual system similarly highlights practical implementation and learning-location cooperation while identifying time and personnel constraints (Hufnagl & Annen, 2026). These adjacent findings strengthen the rationale for authentic, practice-oriented learning, but they are not used here to claim effects specific to Problem-Based Learning.

More direct evidence for problem-based interventions is increasingly available in technical and vocational domains. In electrical/electronic technology education, a quasi-experimental study reported significant positive effects of a problem-based intervention on engagement and practical skills acquisition (Orji, 2025a), while task-based problem scenarios were positively associated with practical skill acquisition in vocational electrical technology (Orji, 2025b). Earlier work also linked PBL experiences with engagement in practical skills and identified intrinsic motivation and ability beliefs as mediating variables (Orji & Ogbuanya, 2022). In automotive vocational education, PBL enhanced by e-learning was associated with improved academic performance, satisfaction, teamwork, and problem-solving competencies in an experimental design (Maksum et al., 2025). STEM-PBL in a higher vocational mathematics course improved engineering students' problem-solving ability (Wang & Somasundram, 2025), and problem-based worksheets increased conceptual understanding among Indonesian vocational students in a one-group pretest–posttest design (Utami et al., 2025). Collectively, these studies support the plausibility of meaningful competence gains under problem-centered instruction.

Evidence remains thinner when the question is narrowed to domain-specific automotive competence. Within the curated reference set, one of the closest studies involved 44 automotive engineering students and compared PBL enhanced by e-learning with conventional instruction, reporting favorable academic and workplace-competency outcomes (Maksum et al., 2025). Another automotive vocational study examined expectations, perceived quality, value, satisfaction, engagement, and critical thinking within a PBL–e-learning ecosystem rather than pre–post technical competence in a specific vehicle system (Wagino et al., 2025). Related engineering studies show that authentic projects can support technical competence in mechatronics and applied engineering contexts (Aishwarya et al., 2024; Tsutsumi, 2025), while contextual and creative problem-solving approaches have been proposed for mechanism and machine science (Krylov &

Devyaterikov, 2023). None of these abstracts addresses brake-system CMS competence among secondary automotive vocational students. The present study therefore occupies a more specific curricular niche: learning change in a safety-critical automotive subsystem within a Grade XI Ototronik class.

A second issue concerns what should count as a meaningful vocational outcome. Competency-based education emphasizes the organization of learning around demonstrable capabilities rather than exposure to content alone. A conceptual model integrating project-oriented problem-based learning with competency-based education identifies learning content, instructional delivery, design, and quality as critical elements in technical and vocational settings (Rahman et al., 2022). In higher vocational education, career-focused project-based learning has been associated with motivation, learning initiative, and vocational skill transformation (Zhang & Yeoh, 2026). Project-based learning in natural contexts has also been linked with improved perceptions of professional competence (Pla-Campas et al., 2025), while competency-focused health-professions research shows how case simulations and structured performance assessment can change students' self-assessed professional competencies (Dymek et al., 2022). Although these studies differ in domain and pedagogy, they converge on an important principle: vocational learning should be evaluated in terms of competence development and application, not only content coverage.

The wider vocational literature also suggests that authentic and learner-centered designs can improve achievement, motivation, and technical capability, but effects depend on implementation. In secondary TVET, a controlled mixed-method study found that project-based learning improved the project-design learning process relative to a comparison group (Isa & Azid, 2021). Self-design project-based learning has been proposed as a way to expose learners to industrially relevant competence requirements (Hamdani & Suherman, 2021), while project work in vocational computing has been associated with computational-thinking skills and project-management capabilities (Habibi et al., 2025). Qualitative work in Indonesian vocational education describes project learning as a vehicle for intellectual, creative, and character development (Kholifah et al., 2025), and combining flipped classroom with project-based learning improved motivation and achievement for some higher-vocational learners (Köpeczi-Bócz, 2024). These studies support active, contextualized learning, but they also caution against treating any PBL label as a uniform intervention detached from task design, facilitation, and assessment.

For the present study, the unresolved issue is not only whether average achievement increases, but whether learning gains are shared across students who begin from different competence levels. Some adjacent evidence indicates that active, collaborative designs may work across learner profiles. E-PBL integrated with design thinking fostered collaboration among both high- and low-self-regulated TVET learners (Nordin et al., 2020). Project-based workforce pathways have also been discussed through an equity and social-mobility lens (Montoya et al., 2021), and an international online project-based engineering experience demonstrated that meaningful professional learning could be organized across participants from diverse geographic and resource contexts (de Maria et al., 2021). However, these studies do not directly test whether a technical class becomes less dispersed as competence increases. Within the curated literature reviewed here, reduction in between-student score dispersion is not foregrounded as a primary outcome.

That gap motivates a distribution-sensitive analysis rather than a conventional comparison of class means alone.

Accordingly, this study examines PBL-supported CMS brake-system instruction among 34 Grade XI Ototronik students using complete paired pre-test and post-test scores. The study asks four questions: (1) How large is the average within-student change? (2) Is improvement broadly distributed or concentrated in a subgroup? (3) How does attainment across increasingly demanding score thresholds change after instruction? and (4) Does between-student dispersion narrow as average performance rises? An exploratory analysis also examines the relation between baseline score and absolute gain. This framing responds to calls for stronger evidence on comparative effectiveness and longer-term PBL outcomes in vocational education (Ibrahim, 2025) while recognizing that design and implementation heterogeneity remains substantial (Sidik et al., 2026). Related work on project-oriented problem-based learning, structured problem-solving modules, and vocational problem-solving programs underscores the value of explicitly linking task design to professional problem solving (Heong et al., 2020; Liangyu et al., 2024; Miliou et al., 2022). The proposed contribution is therefore the concept of competence convergence: an empirically testable pattern in which heterogeneous learners improve while their performance distribution contracts toward high mastery.

METHOD

2.1 Study design and analytical stance

Study design and analytical stance. The available evidence was treated as a one-group pretest–posttest evaluation. Each learner contributed one score before and one score after instruction. The spreadsheet identifies the instructional model as Problem-Based Learning, the subject as Chassis Management System, and the content focus as the brake system. No control or comparison group is present in the dataset. The analysis therefore estimates within-student change over the observed instructional period but does not identify a counterfactual outcome. Statements in this manuscript consequently use terms such as "after PBL-supported instruction," "associated with," and "coincided with" rather than claiming that PBL alone caused the observed gains.

2.2 Participants and dataset

Participants and dataset. The dataset included 34 students labeled as Grade XI Ototronik. All 34 records contained both pre-test and post-test scores, so no cases were excluded for missing outcome data. The score scale was 0–100 as indicated by the values and by the use of 100 as the observed maximum. The spreadsheet did not include student names in the analytical fields used here, demographic characteristics, prior academic indicators, attendance, socioeconomic information, or subgroup identifiers. Accordingly, the analysis is intentionally limited to the paired competence scores and does not infer subgroup effects that the data cannot support.

2.3 Instructional context

Instructional context. The source spreadsheet explicitly records "Model Pembelajaran: Problem Based Learning," "Mata Pelajaran: CMS (Chasis Management System)," and "Materi: Sistem Rem." These labels establish the instructional model and curricular content, but the supplied materials do not document intervention duration, number of lessons, problem scenarios, group size, teacher facilitation procedures, student artifacts, practical workshop activities, or the exact sequence of PBL phases. Those protocol-level variables were therefore not reconstructed or inferred. The findings are interpreted as outcomes observed after the recorded PBL-supported instructional period rather than as evidence about any particular PBL implementation sequence.

2.4 Outcome measure

Outcome measure. The primary outcome was the numerical competence score recorded at pre-test and post-test on the 0–100 scale represented in the dataset. The supplied materials do not identify the assessment format, number of items, weighting of knowledge versus practical performance, scoring rubric, reliability, content-validity process, assessor characteristics, or whether identical or parallel forms were used at the two time points. Consequently, the analysis treats the recorded score as the operational outcome and avoids decomposing it into cognitive and practical subdomains that are not documented. This limitation is considered explicitly when interpreting the term competence. Accordingly, the available study record does not permit the 0–100 score to be classified as a written diagnostic test, a practical workshop performance rubric, or a composite assessment. In addition, 11 of 34 students (32.4%) attained the maximum score of 100 at post-test; therefore, the fixed upper bound creates a potential ceiling effect that can mechanically compress post-test variance and limit discrimination among high-performing learners.

2.5 Research questions and estimands

Research questions and estimands. The primary estimand was the mean within-student change in recorded competence score over the instructional period. Secondary descriptive estimands included the proportion of students with positive gains, the normalized-gain distribution, and the proportion attaining each specified score threshold. The convergence analysis focused on changes in dispersion and on the association between baseline score and raw gain. This hierarchy was selected to distinguish the most defensible result—paired change—from more exploratory interpretations. No subgroup, mediation, moderation, or causal treatment-effect analysis was attempted because the source file does not contain the variables or comparison condition required for such models.

2.6 Primary statistical analysis

Primary statistical analysis. Descriptive statistics were calculated for pre-test scores, post-test scores, and within-student gain scores defined as post-test minus pre-test. For each distribution, the mean, standard deviation, median, interquartile range, minimum, and maximum were examined. The primary inferential test was a paired-samples t-test because the research question concerns the mean within-student change. The normality of difference scores was assessed with the Shapiro–Wilk test. Because the sample is modest and educational scores can show ceiling effects, a one-sided Wilcoxon signed-rank test was also calculated as a non-parametric sensitivity analysis for the direction of improvement. Statistical significance was evaluated at alpha=0.05, although substantive interpretation emphasized confidence intervals and effect magnitude rather than p values alone.

2.7 Effect size and uncertainty

Effect size and uncertainty. The mean difference was accompanied by a 95% confidence interval based on the standard error of the paired differences. Within-participant standardized change was quantified with

Cohen's dz, calculated as the mean difference divided by the standard deviation of the difference scores. A small-sample corrected Hedges-type standardized value was also calculated for sensitivity. Effect-size interpretation was deliberately contextual rather than dependent on categorical labels alone. A large standardized value can arise when change is both large and consistent; it does not, by itself, eliminate threats to internal validity in a one-group design.

2.8 Normalized gain

Normalized gain. To examine the proportion of possible improvement achieved by each student, normalized gain was calculated as (post-test − pre-test)/(100 − pre-test). This metric expresses observed improvement relative to the maximum improvement available from the learner's baseline score. Students were descriptively grouped into low (<0.30), medium (0.30 to <0.70), and high (≥0.70) normalized-gain categories. These categories are used as descriptive aids rather than universal competence standards. They are particularly useful here because absolute gains are constrained by the 100-point ceiling: a learner beginning at 80 cannot improve by more than 20 points, whereas a learner beginning at 25 can improve by as much as 75 points.

2.9 Mastery-threshold analysis

Mastery-threshold analysis. Because vocational education is competence oriented, score changes were also summarized as the proportion of learners meeting a series of score thresholds: 70, 75, 80, 85, 90, 95, and 100. The dataset does not specify an official minimum competency criterion. These thresholds should therefore not be represented as institutional pass standards unless the authors provide documentary confirmation. Instead, they are used to show how the full score distribution shifted from baseline to post-test and to prevent overreliance on a single arbitrary cut point.

2.10 Competence-convergence analysis

Competence convergence analysis. Two complementary indicators were used to characterize convergence. First, the standard deviation and range of pre-test scores were compared with those of post-test scores. A lower post-test dispersion combined with a higher mean is consistent with upward convergence. Second, the relationship between baseline score and absolute gain was evaluated with Pearson's correlation, supplemented by Spearman's rank correlation. A strong negative association indicates that students with lower baseline scores tended to make larger absolute gains. However, such an association is partly induced by mathematical coupling because baseline is included in the gain calculation, and it can also be intensified by ceiling constraints. It is therefore interpreted as a descriptive distributional pattern, not as proof that PBL has a selectively stronger causal effect on initially lower-performing students.

2.11 Data visualization

Data visualization. Four figures were prepared to communicate complementary aspects of the results. Individual paired trajectories show whether improvement was widespread across participants. A distribution plot compares central tendency and spread before and after instruction. A baseline–gain scatterplot visualizes the inverse relation between starting score and absolute change. Finally, threshold-attainment bars show the proportion of students reaching increasingly demanding score levels before and after instruction. Together, these figures are intended to make the central argument visible without duplicating the tables.

2.12 Data quality and reproducibility

Data quality and reproducibility. The analytical dataset contained 34 complete paired observations and no missing values in the two score columns. Scores were checked for admissible values within the 0–100 range. The post-test distribution contained multiple scores of 100, making a ceiling effect plausible. This ceiling is explicitly acknowledged in interpretation of gains and correlations. The raw spreadsheet should be archived with the research record, and the final submission should include a de-identified analytical dataset and analysis syntax if permitted by the target journal and institutional policy.

2.13 Ethics and reporting

Ethics and reporting. The materials supplied for this manuscript contained de-identified classroom-level score records and did not include direct personal identifiers. They did not report an ethics approval or exemption identifier, consent procedures, study dates, participant recruitment procedures, or the teacher–researcher role. These details therefore cannot be asserted from the available evidence. Institutional ethics/authorization and consent information should be confirmed against the original study records before journal submission.

RESULTS AND DISCUSSION

3.1 Results

3.1.1 Participant-level completeness and baseline profile

Participant-level completeness and baseline profile. The dataset contained 34 complete pre–post pairs. No student had a missing pre-test or post-test value. Baseline competence was heterogeneous: scores ranged from 25 to 80, with a mean of 52.35 (SD 13.27), a median of 50, and an interquartile range from 40 to 60. The 55-point baseline range indicates substantial variation in initial mastery. Only five students (14.7%) scored at least 70 before instruction, three (8.8%) scored at least 75, and one (2.9%) scored at least 80. No student scored 85 or above at baseline. These values establish that the class began the observed instructional period with generally modest and uneven performance.

3.1.2 Post-test performance

Post-test performance. After PBL-supported instruction, the score distribution shifted sharply upward. The mean post-test score was 92.65 (SD 7.10), the median was 95, and scores ranged from 75 to 100. The interquartile range was 90–100. Thus, the post-test mean was approximately 40 points higher than the pre-test mean, while the standard deviation was almost halved. The narrowing of the range from 55 points at baseline to 25 points after instruction, together with the lower standard deviation, indicates that performance became more concentrated toward the upper end of the scale.

3.1.3 Magnitude of within-student improvement

Magnitude of within-student improvement. The mean absolute gain was 40.29 points (SD 11.67), with a median gain of 40 points and an observed range from 20 to 65 points. The 95% confidence interval for the mean paired gain was 36.22–44.37 points. Every student recorded a positive difference between post-test and pre-test. Thus, the class-level increase was not generated by a mixture of large improvements and declines; all 34 individual trajectories moved upward. Figure 1 makes this uniform direction of change visible.

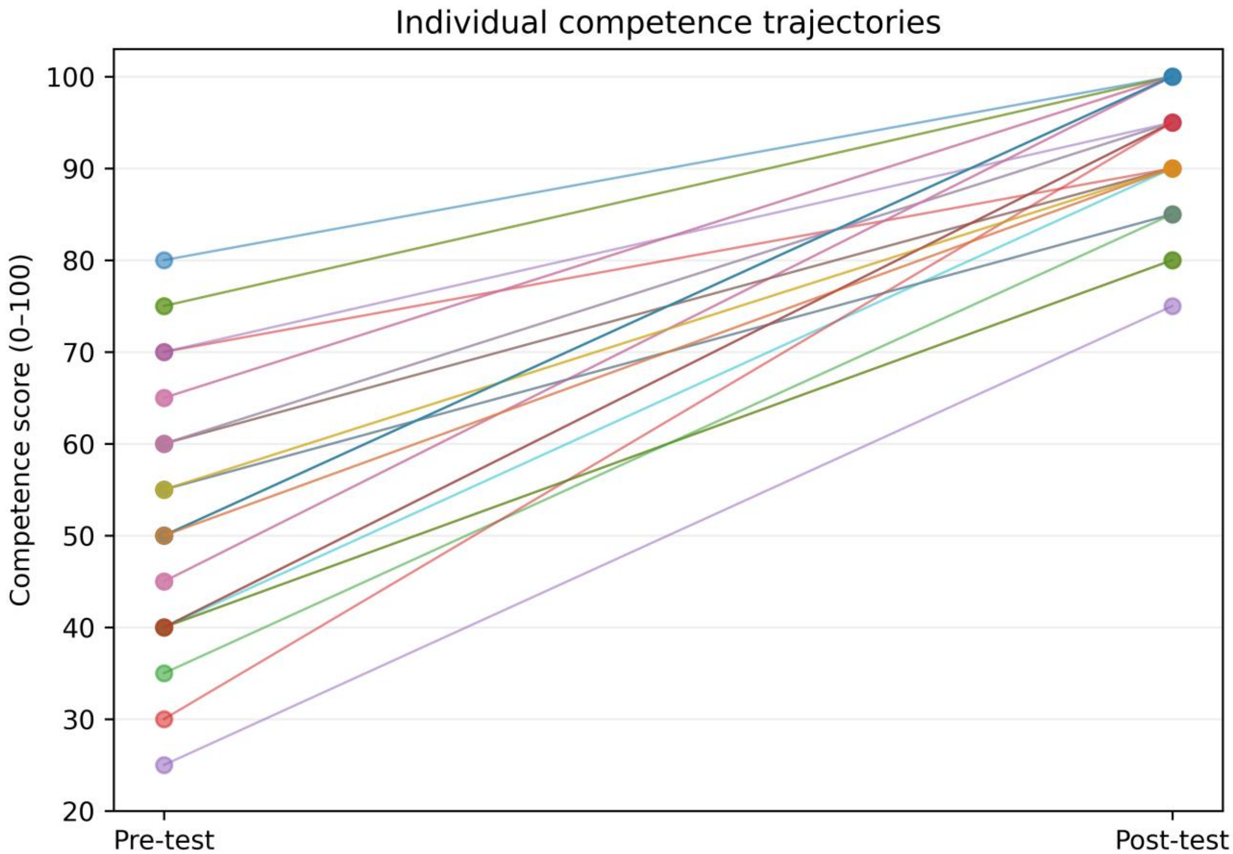

Fig. 1. Individual pre-test and post-test competence trajectories for 34 Grade XI Ototronik students. Every paired trajectory increased after the PBL-supported CMS brake-system instructional period.

3.1.4 Inferential test of the paired difference

Inferential test of the paired difference. Difference scores were approximately compatible with the normality assumption (Shapiro–Wilk W=0.945, p=0.086). A paired-samples t-test showed a very large positive mean difference, t(33)=20.13, p<0.001. The within-participant standardized effect was Cohen's dz=3.45; the small-sample corrected value was approximately 3.37. These estimates indicate that the average change was large relative to the variability of individual change scores. A Wilcoxon signed-rank sensitivity analysis also supported a positive shift (W=595, one-sided p<0.001), showing that the conclusion does not depend solely on the parametric test.

Table 1. Descriptive and inferential summary of pre-test, post-test, and within-student change

Statistic	Pre-test	Post-test	Gain / paired analysis
n	34	34	34 paired
Mean ± SD	52.35 ± 13.27	92.65 ± 7.10	40.29 ± 11.67
Median (IQR)	50 (40-60)	95 (90-100)	40 (31.25-50)
Range	25-80	75-100	20-65
Mean gain, 95% CI	-	-	36.22-44.37
Paired t-test	-	-	$t(33)=20.13$; $p<0.001$
Cohen's dz	-	-	3.45
Hedges-corrected standardized change	-	-	3.37
Wilcoxon sensitivity analysis	-	-	W=595; one-sided $p<0.001$
Normalized gain, mean ± SD	-	-	0.855 ± 0.129

Note. CI, confidence interval; IQR, interquartile range; SD, standard deviation. Shapiro-Wilk test of gain-score normality: W=0.945, p=0.086.

3.1.5 Normalized gains

Normalized gains. Mean normalized gain was 0.855 (SD 0.129), with a median of 0.875 and a range from 0.667 to 1.000. Using the descriptive thresholds specified in the Methods, 27 of 34 students (79.4%) were in the high normalized-gain category and seven (20.6%) were in the medium category; none was in the low category. This result is important because normalized gain adjusts the raw improvement for the amount of score space available above each student's baseline. Learners beginning at comparatively high pre-test levels still had less numerical room to improve, but all students reached at least a medium normalized gain.

3.1.6 Mastery-threshold movement

Mastery-threshold movement. Threshold analysis showed a marked change in the proportion of learners attaining high scores. At baseline, 14.7% reached at least 70 and 8.8% reached at least 75. After instruction, all 34 students reached at least 75. At the 80-point threshold, attainment increased from 2.9% to 97.1%. At 85, attainment increased from 0% to 88.2%; at 90, from 0% to 79.4%; and at 95, from 0% to 55.9%. Eleven students (32.4%) achieved the maximum observed score of 100 at post-test. Table 2 and Fig. 2 summarize these distributional shifts.

Table 2. Proportion of students attaining selected score thresholds before and after instruction.

Score threshold	Pre-test, n (%)	Post-test, n (%)	Change, percentage points
≥70	5 (14.7%)	34 (100.0%)	85.3
≥75	3 (8.8%)	34 (100.0%)	91.2
≥80	1 (2.9%)	33 (97.1%)	94.1
≥85	0 (0.0%)	30 (88.2%)	88.2
≥90	0 (0.0%)	27 (79.4%)	79.4
≥95	0 (0.0%)	19 (55.9%)	55.9

Score threshold	Pre-test, n (%)	Post-test, n (%)	Change, percentage points
≥100	0 (0.0%)	11 (32.4%)	32.4

Note. Thresholds are descriptive score cut points. The source dataset does not identify an official institutional competency/pass criterion.

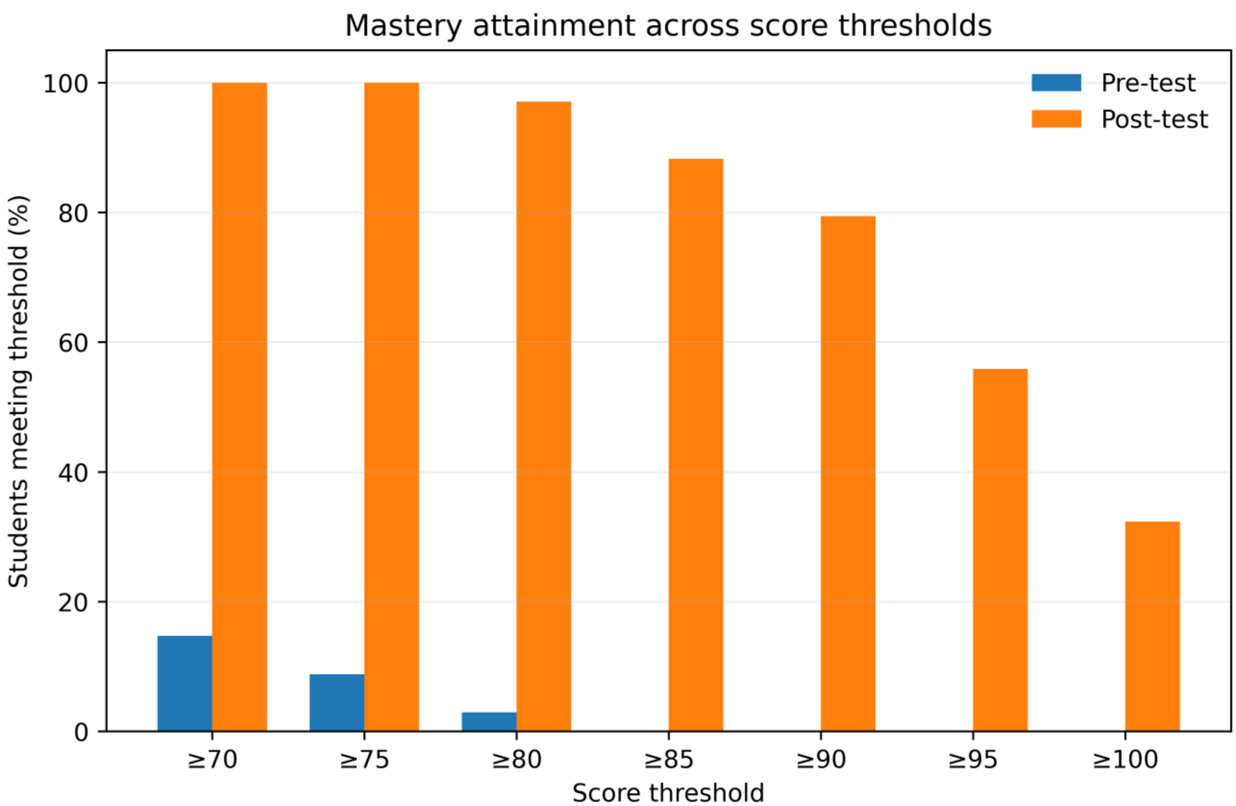

Fig. 2. Percentage of students meeting increasingly demanding score thresholds at pre-test and post-test. Thresholds are descriptive and are not represented as official pass criteria.

3.1.7 Individual trajectories and distributional shift

Individual trajectories and distributional shift. Fig. 1 shows that all paired lines rise from pre-test to post-test, providing a visual check on the universality of improvement. Fig. 3 shows that the center of the post-test distribution moved upward while the distribution compressed near the upper score boundary. The post-test box is positioned between 90 and 100, compared with a baseline interquartile span of 40–60. The presence of repeated post-test scores at 100 is visible and should be interpreted as evidence of high attainment combined with a potential ceiling effect.

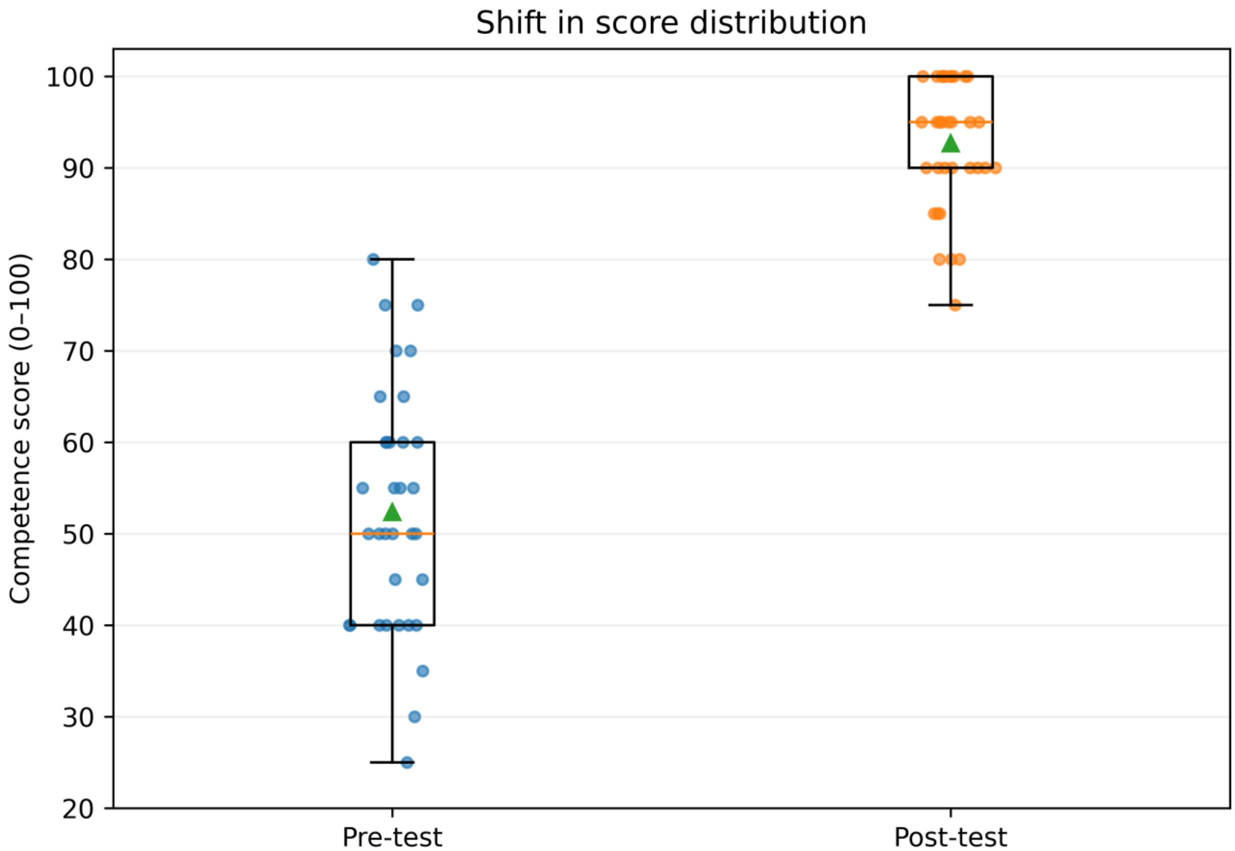

Fig. 3. Distribution of CMS competence scores before and after PBL-supported instruction. Boxplots show the median and interquartile spread; points show individual observations. Repeated scores at 100 indicate a possible post-test ceiling effect.

3.1.8 Baseline score and absolute gain

Baseline score and absolute gain. Pre-test score was strongly and inversely correlated with absolute gain (Pearson $r=-0.846$, $p<0.001$; Spearman $\rho=-0.862$, $p<0.001$). The estimated linear relation corresponded to a decrease of approximately 0.74 gain points for each one-point increase in baseline score. Fig. 4 shows that students who began with lower scores frequently achieved gains of 45–65 points, whereas those starting near 70–80 had smaller absolute gains because they were already closer to the maximum score. This pattern is consistent with upward competence convergence but must not be interpreted as an unbiased treatment–baseline interaction because absolute gain contains the baseline term and because the assessment has an upper limit of 100.

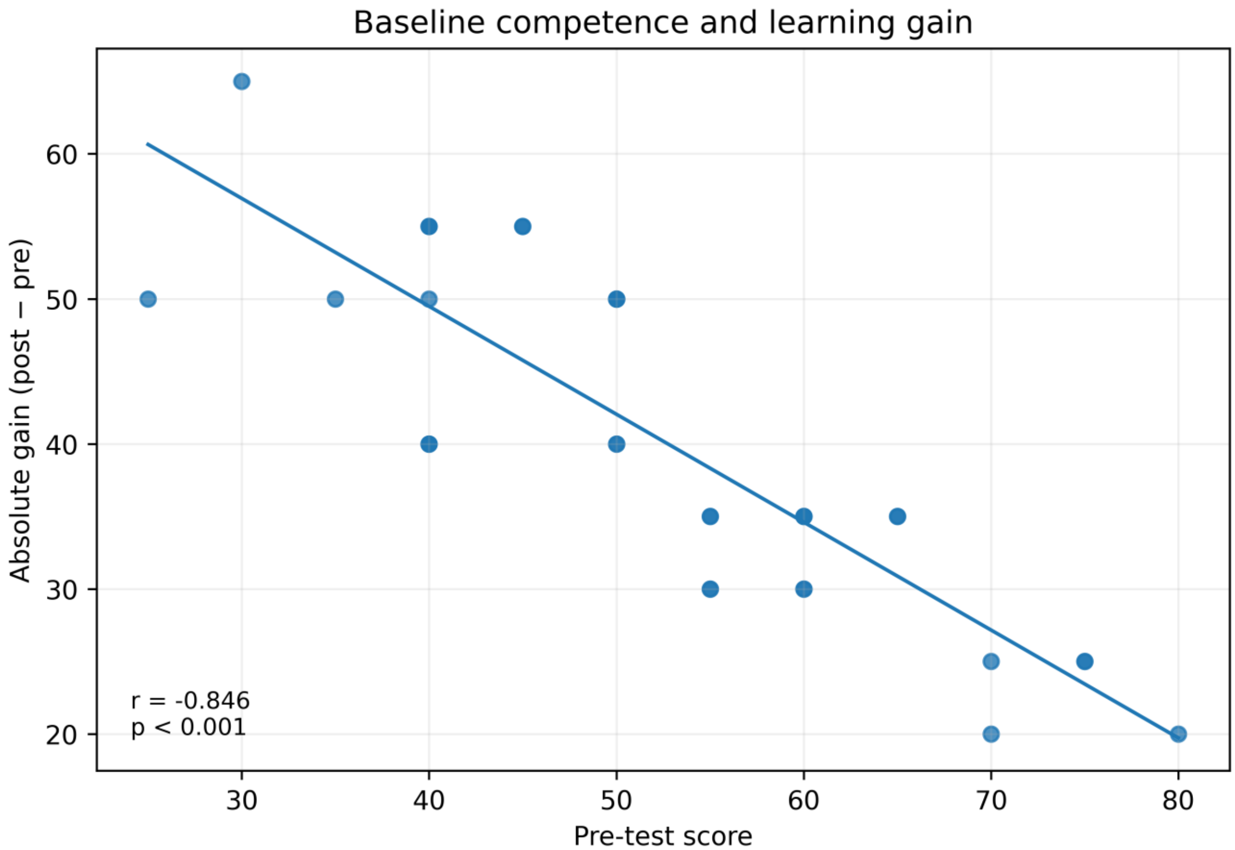

Fig. 4. Association between baseline competence and absolute learning gain. Lower baseline scores were associated with larger raw gains (Pearson $r=-0.846$, $p<0.001$). Interpretation should account for mathematical coupling and the 100-point ceiling.

3.1.9 Overall empirical pattern

Overall empirical pattern. Taken together, the results show four mutually reinforcing features: a large increase in average competence, universal positive within-student change, movement of nearly the whole cohort into high score ranges, and reduced dispersion at post-test. The findings therefore support the descriptive proposition that the observed PBL instructional period was characterized by competence convergence. The data do not establish whether the same students would have improved similarly under conventional instruction, another active-learning model, repeated practice, or ordinary curricular progression. That causal question requires a comparative design.

3.2 Discussion

3.2.1 Principal findings: from improvement to competence convergence

The present study documented a pronounced shift in the competence profile of the Grade XI Ototronik cohort. Mean CMS brake-system scores increased from 52.35 before instruction to 92.65 after instruction, and the mean paired gain was 40.29 points. Every learner improved. This direction is consistent with problem-based evidence from other technical domains, where practical-skill performance, engagement, conceptual understanding, or problem-solving ability improved after structured problem-centered instruction (Orji, 2025a; Utami et al., 2025; Wang & Somasundram, 2025). Automotive evidence is especially relevant: an experimental study of PBL enhanced by e-learning reported favorable academic and workplace-competency outcomes among automotive engineering students (Maksum et al., 2025). The present effect cannot be equated directly with those studies because the intervention, assessment, sample, and design differ, but the convergence of direction strengthens the interpretation that problem-centered technical instruction can support substantial learning. The unusually large within-participant effect observed here should therefore be read as a description of this cohort's change, not as a universal estimate of PBL effectiveness.

The most distinctive result is distributional rather than merely average. Pre-test scores ranged from 25 to 80 with SD=13.27, whereas post-test scores ranged from 75 to 100 with SD=7.10. Thus, the class became both higher-performing and less dispersed. This pattern motivates the term competence convergence. The idea is compatible with evidence that well-designed problem-oriented environments can support different learner profiles: e-PBL combined with design thinking fostered collaboration among both high- and low-self-regulated TVET learners (Nordin et al., 2020), while career-focused project-based learning has been linked to motivation, initiative, and vocational skill transformation (Zhang & Yeoh, 2026). Neither finding is equivalent to reduced score dispersion, but both suggest that active vocational designs can be analyzed in terms of who benefits, not only whether a mean changes. In a competence-oriented classroom, narrowing the lower tail while maintaining high attainment can be educationally important because occupational readiness depends on bringing all learners toward a defensible performance standard.

Individual trajectories reinforce this interpretation. All 34 paired lines moved upward and the smallest raw gain was 20 points. Mean normalized gain was 0.855; 79.4% of students were classified as high gain and the remaining 20.6% as medium gain. These results make it unlikely that the mean increase was driven by a small number of exceptional responders. Positive learning patterns have also been reported in technical settings where Problem-Based Learning supported autonomous work among engineering students (Bilbao et al., 2024), and where PBL-based vocational interventions strengthened engagement and practical skills (Orji, 2025a). The present study extends that logic by showing the full distribution of individual changes. Rather than treating variability as statistical noise around an average effect, the analysis makes heterogeneity itself part of the substantive outcome. This is particularly appropriate for vocational education, where nonresponse or persistent low attainment can have practical implications even when the class mean appears satisfactory.

The inverse association between baseline score and absolute gain ($r=-0.846$) is central to the convergence narrative but should not be interpreted as evidence that PBL causally benefits lower-performing students more. Absolute gain contains the baseline score in its calculation, so mathematical coupling can induce a negative relationship. The 100-point upper bound also restricts the improvement available to students who begin near the top, and measurement error can produce regression-to-the-mean effects. The defensible conclusion is narrower: in this cohort, low initial scores did not prevent students from attaining high post-test values, and the observed distribution compressed upward. A stronger claim about differential treatment response would require a comparison group, repeated measures, or models that separate baseline measurement error from true change. This restraint is important because the same visual pattern—larger raw gains among lower scorers—can arise from both genuine instructional equalization and purely statistical constraints.

3.2.2 Pedagogical interpretation in automotive vocational education

The competence gains are pedagogically plausible because problem-based instruction creates a reason to integrate knowledge rather than encounter concepts as isolated facts. Engineering-oriented PBL programs have been designed explicitly around professional problem-solving processes and have reported deeper understanding of problem solving and professional knowledge (Miliou et al., 2022). Modules that integrate creative and critical thinking into PBL similarly emphasize structured problem solving in technical and vocational education (Heong et al., 2020), while a recent systematic review identifies problem-based learning and critical questioning among strategies associated with critical-thinking development in vocational contexts (Nurtanto et al., 2026). In practical technology education, intrinsic motivation and ability beliefs have also been identified as mechanisms linking PBL experiences to engagement in skills acquisition (Orji & Ogbuanya, 2022). These studies provide plausible mechanisms for the current results: authentic brake-system problems may have prompted students to retrieve prior knowledge, identify gaps, compare diagnostic explanations, and justify decisions. The dataset does not contain process measures, however, so these mechanisms remain interpretations to be tested rather than observed mediators.

The findings also have implications for curriculum sequencing. When students enter a technical unit with widely different prior knowledge, one response is to reteach prerequisite content before allowing application. A problem-oriented alternative is to use an authentic task to expose what knowledge is needed and then provide targeted explanation or practice at the point of need. Indonesian vocational research has described contextual and problem-based approaches as ways to strengthen life skills through learning connected to real problems (Malaikosa et al., 2020). Project-based engineering studies likewise argue that real problem situations can help learners develop technical competence through practical application (Mukunda Vani et al., 2021). Technology-enriched problem-case instruction has been used in vocational education to increase engagement and motivation through gamification and augmented reality (Wulansari et al., 2024), while a problem-based blended-learning model in vocational computer-network engineering demonstrated moderate learning gain alongside reported validity and practicality (Maksum et al., 2023). These adjacent findings do not verify the mechanism in the present class, but they support a design principle: scaffolding should be embedded within purposeful technical activity rather than separated completely from it. The final instructional protocol should therefore document when conceptual input, peer discussion, diagnostic reasoning, and feedback occurred.

Brake-system learning is particularly suitable for a problem-centered approach because competence is relational and safety sensitive. Learners must connect symptoms to hydraulic, mechanical, frictional, and possibly electronic causes; prioritize inspection steps; distinguish likely from unlikely explanations; and consider the consequences of incorrect diagnosis. The two most directly relevant automotive studies in the curated literature used PBL integrated with e-learning and reported gains in academic outcomes, problem-solving, critical thinking, perceived value, or satisfaction (Maksum et al., 2025; Wagino et al., 2025). Related authentic engineering projects have supported technical competence in mechatronics and power-electronics contexts (Aishwarya et al., 2024; Tsutsumi, 2025). The current study adds a narrower curricular case—secondary-level CMS brake-system instruction—and a different analytical emphasis. Its contribution is not evidence that PBL is uniquely effective for brakes, but evidence that a problem-based instructional period coincided with large gains and a compressed post-test competence distribution in this specialized automotive domain.

3.2.3 Practical meaning, thresholds, and measurement ceiling

The standardized change was exceptionally large: Cohen's dz=3.45, with a 95% confidence interval for the raw mean gain of 36.22–44.37 points. Such a value indicates that the average increase was large relative to the variability of individual change scores. It should not be interpreted as a causal effect size comparable to a between-group standardized mean difference. In a one-group pretest–posttest design, history, maturation, testing, repeated exposure, teacher effects, and ordinary curricular progression remain viable alternative explanations. The Wilcoxon sensitivity analysis strengthens confidence that the direction of change is not an artifact of normality assumptions, but it does not solve the counterfactual problem. This distinction is important when situating the results beside quasi-experimental or controlled studies in vocational education, including work showing positive effects of problem-based interventions on practical skills (Orji, 2025a) and STEM-PBL on problem-solving ability (Wang & Somasundram, 2025). The present statistics describe a strong within-class transformation; they do not establish superiority over an unobserved comparison pedagogy.

The threshold analysis gives the statistical change a more concrete educational interpretation. Before instruction, only three students scored at least 75 and only one reached 80; after instruction, all 34 scored at least 75 and 33 reached 80 or above. At 90, 27 students met the threshold. These values are descriptive rather than official pass rates because the source materials do not specify an institutional competency criterion. Even so, the pattern is relevant to competency-based education, where the practical question is whether learners approach specified capabilities rather than simply whether a mean difference is significant. Work integrating project-oriented problem-based learning with competency-based education similarly emphasizes alignment among learning content, instructional delivery, design, and competency requirements (Rahman et al., 2022). The current threshold analysis translates the score shift into an attainment profile and makes visible how many learners occupy increasingly demanding performance zones. For vocational readers, that distribution may be more interpretable than p values alone.

High attainment also creates a measurement problem. Eleven students reached 100 and the upper quartile of post-test scores was at the scale maximum. A ceiling can compress variance and prevent the assessment from distinguishing advanced levels of competence, thereby exaggerating the appearance of convergence. The post-test reduction in standard deviation is therefore substantively interesting but cannot be assumed to represent an equivalent reduction in latent competence variation. Future assessments should include sufficiently difficult diagnostic items or performance tasks to discriminate among high-performing learners. Where possible, multiple forms of evidence—conceptual tests, diagnostic case analysis, procedural performance, and assessor-rated practical tasks—should be combined. This is particularly important because vocational competence is broader than a single written score, and the source file does not specify whether the instrument measured knowledge, diagnosis, practical execution, or a composite of these domains.

3.2.4 Conceptual contribution and literature-integration agenda

Measurement validity is consequently central to the manuscript's contribution. The available dataset supplies paired scores but not an item blueprint, rubric, reliability estimate, content-validation procedure, or evidence that pre-test and post-test forms were equivalent. If the assessment primarily measured written knowledge, the outcome should be described as CMS brake-system achievement rather than comprehensive occupational competence. If it included diagnostic reasoning or practical performance, the manuscript should report how those domains were sampled and scored. This construct discipline matters because studies in vocational education often use different outcome types, from perceived professional competence (Pla-Campas et al., 2025) to practical skill performance (Orji, 2025a) and conceptual understanding (Utami et al., 2025). The present label "competence" is justified only to the extent that the underlying assessment captures the competence construct intended by the curriculum. A stronger instrument description would therefore increase both internal interpretability and comparability with the literature. Accordingly, the present analysis interprets the 0–100 measure as a recorded operational score rather than assuming a written, practical, or composite assessment composition that is not documented. The convergence interpretation must also be tempered by the 100-point ceiling because 11 students (32.4%) were at the maximum, a boundary condition that can mechanically reduce observed post-test variance independently of any true reduction in latent competence differences.

The study nevertheless offers a conceptual contribution by treating distributional equity as part of instructional effectiveness. Adjacent project-based studies have reported improvements in independence, technical understanding, or skill development in vocational and polytechnic contexts (Tokoš et al., 2025; Vijay et al., 2025). Other work emphasizes the role of authentic projects in developing professional or technical competence (Hamdani & Suherman, 2021; Tsutsumi, 2025). These studies typically foreground mean outcomes, perceptions, or qualitative experiences. The competence-convergence lens asks an additional question: does the instructional experience reduce the proportion of learners who remain far below the high-performance region? In this dataset, the answer descriptively is yes. The mean rose sharply, all learners improved, and dispersion declined. This framing does not require claiming that every learner became identical; rather, it emphasizes movement toward a narrower zone of high attainment. For competency-oriented systems, such a distribution-sensitive outcome may be as policy-relevant as an average gain.

The curated literature also clarifies the novelty boundary. Bibliometric work identifies growing interest in project-based learning across vocational and STEM education while pointing to gaps in longitudinal and comparative evidence (Ibrahim, 2025). A systematic review of applied-science project-based learning shows substantial variation in instructional design and identifies student readiness, teacher readiness, time, collaboration, and resources as implementation challenges (Sidik et al., 2026). Problem-based vocational studies in the supplied set demonstrate gains in engagement, practical skills, conceptual understanding, or problem-solving, but none of the selected abstracts foregrounds pre–post reduction in score dispersion as the central outcome. The present article therefore should not claim to introduce the first ever analysis of convergence; the literature set is curated rather than exhaustive. A defensible novelty statement is that this study applies an explicitly distribution-sensitive competence-convergence analysis to CMS brake-system learning, thereby extending the usual emphasis on average learning outcomes within the evidence base available for this manuscript.

3.2.5 Future research design and mechanism testing

Future research should test the mechanisms that could generate the observed convergence pattern. Motivation is one candidate: ability beliefs and intrinsic motivation have been reported as mediators between PBL experience and practical-skill engagement (Orji & Ogbuanya, 2022), while career-focused project-based learning has linked motivation to learning initiative and vocational skill development (Zhang & Yeoh, 2026). Collaboration is another candidate, given evidence that e-PBL with design thinking can foster collaboration across self-regulation profiles (Nordin et al., 2020). Instructor support may also matter; vocational research in tourism education identified teacher assistance as a mediator in relationships involving PBL effectiveness and student outcomes (Wen & Sumettikoon, 2024). In automotive education, perceived quality and value are associated with satisfaction in PBL–e-learning environments (Wagino et al., 2025). A future CMS study could therefore collect process data on motivation, self-efficacy, collaboration, teacher scaffolding, and diagnostic reasoning alongside achievement. Mediation or process-tracing analyses could then distinguish plausible mechanisms from post hoc interpretation.

The most important design extension is a credible comparison condition. Controlled and quasi-experimental vocational studies demonstrate that such designs are feasible: project-based TVET has been compared with a control group using ANCOVA (Isa & Azid, 2021), problem-based practical-skills interventions have used intervention and control groups with multivariate analysis (Orji, 2025a), and STEM-PBL has been evaluated with experimental and control groups in higher vocational education (Wang & Somasundram, 2025). Automotive research has also compared PBL enhanced by e-learning with conventional instruction (Maksum et al., 2025). A future CMS study should therefore compare PBL with a well-specified alternative while holding curriculum content, instructional time, assessment, and instructor expertise as constant as practical. Repeated post-tests would determine whether convergence persists beyond immediate testing. Such work would directly address the broader literature's concern with comparative effectiveness and longer-term outcomes (Ibrahim, 2025).

Multi-class and multi-site replication is equally important. The present sample contains 34 students from one Grade XI Ototronik class, so class culture, teacher expertise, facilities, and local curriculum conditions cannot be separated from the instructional model. Implementation research shows that vocational PBL depends on institutional conditions. Stakeholders have identified resource limitations, teacher capacity, and difficulty identifying authentic problems as barriers to PBL in TVET (Kissi et al., 2020; Okolie et al., 2021).

School-level studies of project-based learning emphasize leadership, collaboration, resources, and professional development (Figueroa et al., 2023; González et al., 2026), while dual-system evidence identifies time, personnel, and learning-location cooperation as practical constraints (Hufnagl & Annen, 2026). Replicating the CMS design across schools would allow researchers to estimate how much competence gain and convergence vary by instructor, class, and institutional context, rather than assuming that one implementation represents PBL as a stable treatment.

3.2.6 Strengths, limitations, and implications

Several limitations constrain inference. First, there is no comparison group, so the study estimates observed within-student change rather than the causal effect of PBL. Second, the source materials do not provide the intervention duration, problem scenarios, group organization, facilitation protocol, or fidelity indicators. Third, the assessment instrument is insufficiently documented to establish how well the scores represent comprehensive CMS competence. Fourth, the post-test ceiling may compress variance and contribute to the convergence pattern. Fifth, the sample is small and context specific, and no demographic, attendance, prior-achievement, motivation, or workshop-experience variables are available. Finally, the baseline–gain correlation is vulnerable to mathematical coupling and regression to the mean. These limitations are substantive rather than cosmetic: they define which claims are defensible. The study can strongly describe what happened to the recorded scores during the instructional period, but it cannot establish why the change occurred or whether the same pattern would exceed that produced by another competent teaching approach.

Within those boundaries, the evidence has several strengths. All 34 learners contributed complete paired observations, eliminating missing-outcome complications within the supplied dataset. The average gain is large on the original 0–100 scale, its confidence interval is narrow relative to its magnitude, and parametric and non-parametric analyses agree on the direction of change. The result is also supported by multiple complementary summaries: every individual improved, normalized gains were uniformly medium or high, threshold attainment shifted sharply upward, and post-test dispersion declined. This triangulation reduces dependence on a single inferential statistic. The analysis also explicitly acknowledges the ceiling and avoids treating $p<0.001$ as sufficient proof of educational importance. For an exploratory classroom study, this combination of effect magnitude, individual trajectories, and distributional analysis provides a stronger descriptive foundation than a simple pre–post mean comparison.

The competence-convergence concept should therefore be presented as a disciplined empirical proposition. It describes a class that began with a wide range of CMS scores and ended with a narrower range near the top of the assessment scale. It does not imply that PBL universally equalizes learners, that low-performing students benefit more in causal terms, or that all students reached equivalent practical competence. The value of the concept is analytical: it directs attention to the shape of learning gains and to the lower tail of the performance distribution. This is consistent with the broader vocational concern that pedagogy should produce usable capabilities across diverse learners rather than merely improve average achievement. The next evidentiary step is to test whether convergence is larger, more durable, and more transferable under PBL than under credible alternatives.

For practice, the findings support continued investigation of authentic problem-centered instruction in automotive vocational education, especially when classes contain heterogeneous starting knowledge. Effective implementation should combine technically meaningful problems with deliberate scaffolding, access to practical resources, opportunities for collaborative reasoning, and assessment that rewards explanation and diagnosis. Learner accounts in vocational computing emphasize hands-on work, collaboration, self-directed exploration, and challenge in practical learning (Bascuguin & Generoso, 2026), while TVET research identifies problem-based and active-learning principles as important elements of quality pedagogy (Okolie et al., 2023). Active-learning work in vocational chemistry similarly stresses the potential of problem-based learning, simulation, and collaboration while noting institutional and faculty-readiness barriers (Qi et al., 2024). For CMS instruction, the implication is not to adopt PBL as a label, but to design problems that genuinely require system reasoning and to document how students move from symptom recognition to evidence-based diagnosis.

Overall, the manuscript advances from an achievement-improvement claim to a competence-convergence argument. The first level of evidence is the 40.29-point mean gain. The second is the universality of positive change. The third is the movement of nearly the whole cohort into high score ranges. The fourth is reduced dispersion after instruction. Considered together, these results depict a class that became not only better performing on average but also more consistently high performing on the recorded assessment. The literature synthesized here shows that problem-based and adjacent authentic-learning approaches can support engagement, problem solving, practical skills, motivation, and vocational competence across technical domains, while also highlighting implementation variability and the need for stronger comparative evidence. The present study contributes a focused automotive case and a distribution-sensitive analytical lens. Its strongest claim is therefore precise: PBL-supported CMS brake-system instruction coincided with large, universal learning gains and upward competence convergence, a pattern that now warrants controlled replication using richer measures of authentic technical performance.

CONCLUSION

Problem-Based Learning-supported instruction in Chassis Management System brake-system material was followed by a large and highly consistent increase in competence scores among 34 Grade XI Ototronik students. Mean performance rose from 52.35 to 92.65, producing a mean paired gain of 40.29 points (95% CI 36.22–44.37), $t(33)=20.13$, $p<0.001$, with Cohen's $d_z=3.45$. Every student improved, 79.4% achieved a high normalized gain, and the remainder achieved a medium gain. At the same time, post-test scores were less dispersed than baseline scores and the great majority of students moved into high score ranges.

The most informative interpretation is therefore not simply that the class average increased. The observed learning period was characterized by upward competence convergence: students who entered with widely different baseline scores finished with a comparatively narrow distribution of high performance. Lower baseline scores were associated with larger absolute gains, although this pattern must be interpreted in light of mathematical coupling, regression to the mean, and ceiling constraints. The convergence construct is consequently descriptive rather than causal.

The study adds a distribution-sensitive perspective to the literature on problem-centered vocational learning and provides focused evidence from secondary automotive CMS education, a context that is sparsely represented in the curated evidence base. However, the absence of a comparison group, limited documentation of the intervention and assessment instrument, and the post-test ceiling restrict causal and construct-level inference. Future multi-class studies should compare PBL with credible alternative pedagogies, document implementation fidelity, use assessments that capture authentic diagnostic and practical performance, and include delayed testing to determine whether competence convergence is specific to PBL and persists beyond immediate post-instruction measurement.

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