



## STEM-Based Teaching Module with a Realistic Mathematics Education Approach to Improve Critical Thinking Skills among Vocational High School Students in an Automotive Engineering Program

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Received: May 2026; Revised: June 2026; Published: July 2026

### Abstract

This study aimed to examine the effectiveness of a STEM-based teaching module with a Realistic Mathematics Education (RME) approach in improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program. The study employed a mixed-methods approach with an explanatory sequential design. The quantitative phase was conducted through a quasi-experiment using a pretest-posttest control group design, while the qualitative phase was conducted through semi-structured interviews with mathematics teachers. The participants were 62 eleventh-grade Motorcycle Engineering students at SMK Negeri 1 Pringgabaya, consisting of 31 students in the experimental group and 31 students in the control group. The experimental group received instruction using the STEM-RME-based teaching module, whereas the control group received expository instruction. The quantitative instrument was a written test consisting of 15 multiple-choice items and 5 open-ended questions. The data were analyzed using descriptive statistics, gain scores, N-Gain, paired-samples t-test, independent-samples t-test, mixed-design ANOVA, and thematic analysis. The results showed that the mean score of the experimental group increased from 22.39 to 28.97, while that of the control group increased from 22.23 to 24.87. The mean N-Gain of the experimental group was 0.53, categorized as moderate, whereas that of the control group was 0.20, categorized as low. The paired-samples t-test showed a significant improvement in the experimental group,  $t(30) = 27.95$ ,  $p < 0.001$ , and in the control group,  $t(30) = 7.52$ ,  $p < 0.001$ . The independent-samples t-test showed significant differences in the posttest score,  $t(56.81) = 11.20$ ,  $p < 0.001$ , gain score,  $t(60) = 9.30$ ,  $p < 0.001$ , and N-Gain,  $t(60) = 9.64$ ,  $p < 0.001$ . The mixed-design ANOVA revealed a significant time  $\times$  group interaction,  $F(1,60) = 86.43$ ,  $p < 0.001$ . The teacher interview findings indicated that students found it easier to understand mathematical concepts when the material was connected to automotive contexts, such as wheels, tires, rims, disc brakes, gears, sprockets, pulleys, and tangent lines on vehicle components. The teachers also emphasized that real-life contexts, teaching aids, modeling, discussion, and visualization helped students overcome difficulties in visualizing geometry and encouraged them to provide reasoning and check the reasonableness of their answers. Thus, the STEM-RME-based teaching module was effective in improving students' critical thinking skills.

**Keywords:** Realistic mathematics education; Critical thinking; STEM education; Vocational education; Automotive engineering

**How to Cite:** Alaydrus, K. A., Sutarto, S., & Prayogi, S. (2026). STEM-Based Teaching Module with a Realistic Mathematics Education Approach to Improve Critical Thinking Skills among Vocational High School Students in an Automotive Engineering Program. *Prisma Sains: Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, 14(3), 1050–1081. <https://doi.org/10.33394/j-ps.v14i3.21001>



<https://doi.org/10.33394/j-ps.v14i2.21001>

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## INTRODUCTION

STEM education, which stands for Science, Technology, Engineering, and Mathematics, is increasingly regarded as a highly relevant approach for preparing students to face the challenges of a rapidly changing and technology-intensive labor market. In the continuously evolving digital era, STEM education plays an important role in developing

students' problem-solving abilities, creativity, and critical thinking skills (Akcan et al., 2023). The integration of STEM principles into learning can improve graduates' employment prospects because they become more adaptive to the demands of new technologies and better prepared to face industrial dynamics that require both technical and non-technical skills simultaneously (Swafford, 2018). Furthermore, this approach does not only focus on content mastery in science, technology, engineering, and mathematics, but also on the development of generic skills such as communication, teamwork, and adaptability, which are highly needed in today's workplace (Aunzo, 2024; Villán-Vallejo et al., 2022).

However, the benefits of STEM education depend greatly on the quality of its implementation at the school level. Several studies have shown that claims regarding the benefits of STEM cannot simply be assumed to always produce positive outcomes without contextual investigation and more in-depth evaluation of its implementation in practice (Rothman & Sisman, 2016). Therefore, the success of STEM education in producing work-ready graduates depends heavily on the quality of teaching, curriculum, and industry involvement in the educational process. The connection between educational institutions and industry is one of the important factors supporting STEM implementation, including in vocational fields such as vocational high schools (O'Dea et al., 2024). Collaboration through internships, project work, or work-based learning has been reported to reduce the gap between theoretical knowledge acquired in the classroom and practical experience in the field (Kelly et al., 2023).

Experiential learning systems provide opportunities for students to test and modify the knowledge they learn in the classroom within real-world contexts. This aims to develop skills that can be transferred to more diverse and complex work situations, such as those required in the automotive industry (Swafford, 2018; Bloomberg, 2024). However, the challenge is that not all educational institutions, especially those in certain regions, have equal access to strong industry partners that can provide students with optimal industry-based learning experiences.

In the context of vocational education, particularly in automotive engineering programs at vocational high schools, STEM education faces the challenge of aligning the curriculum with the rapid technological developments in the automotive industry. The integration of modern technology, increasingly strict environmental regulations, and shifting consumer preferences toward more efficient and environmentally friendly vehicles require automotive education programs not only to teach basic technical skills in operating and maintaining conventional vehicles, but also to develop skills in understanding and analyzing current automotive technologies, such as electric vehicles and automation systems (Lim & Wong, 2025; Onwusa & Asuai, 2025). Automotive engineering education in vocational high schools must also prepare graduates who are able to adapt to changes and new technologies in the automotive industry, in line with the demands of Industrial Revolutions 4.0 and 5.0 (Wagino, 2025; Wannapiroon et al., 2021). Therefore, a more holistic approach to mathematics education is crucial so that students do not merely understand theory, but are also able to apply mathematical skills to solve real-world problems in the automotive industry.

Realistic Mathematics Education (RME) is one approach proposed to bridge mathematics learning with real-world contexts, particularly in automotive engineering. This approach emphasizes the use of authentic contexts and the process of "mathematization" from real-world situations into mathematical representations that can be applied practically in everyday life (Zakaria & Syamaun, 2017). In the automotive context, for example, calculations of fuel consumption, gear ratio analysis, or estimation of vehicle maintenance costs can serve as entry points for developing mathematical models that are relevant to the industrial world. This approach not only engages students in problem solving, but also facilitates them to think critically about the solutions they choose and to develop the analytical skills needed in the workplace (Bal & Kapucu, 2022). This is important considering that

today's automotive industry places strong emphasis on rapid innovation and technological development, requiring workers in this field to possess higher-order thinking skills in identifying and solving complex problems (Sugiarto et al., 2022).

However, the implementation of RME in automotive engineering education requires more than the use of automotive examples in mathematics lessons. It requires teachers to have a deep understanding of both mathematical content and the vocational automotive context they teach, as well as the ability to facilitate students in critical and reflective thinking processes (Edo & Tasik, 2019). In addition, the successful implementation of RME in automotive vocational education depends heavily on adequate training support for teachers and collaboration with industry to ensure the relevance and applicability of the contexts used in learning (FitzSimons, 2014; Morales-Doyle, 2017). Therefore, this study aims to develop a STEM-based teaching module with an RME approach focused on improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program at SMK Negeri 1 Pringgabaya, East Lombok Regency, West Nusa Tenggara Province.

The teaching module developed in this study aims to integrate STEM principles with the RME approach, which is expected to improve students' critical thinking skills in the context of automotive engineering. This study examines the effectiveness of implementing this learning model in improving students' critical thinking skills, as well as the factors that influence such improvement during the learning process. Thus, this study is expected to make an important contribution to the development of curriculum and learning strategies in vocational high schools, particularly in automotive engineering, to prepare graduates who not only possess technical skills but also higher-order thinking skills needed in the continuously developing automotive industry.

Scholars emphasize that STEM education plays an important role in improving students' critical thinking and problem-solving skills across various educational contexts. A meta-analysis concluded that the STEM approach can promote critical thinking, problem solving, creativity, collaboration, and systems thinking skills in 21st-century learning, all of which are highly needed by students to face global challenges and the complexity of the workplace (Nur Rarastika et al., 2025).

Ion Mierluș-Mazilu and Fatih Yilmaz (2023), in their study, emphasized that mathematics teaching in the STEM context is essential for developing students' analytical and logical abilities, which are central to critical thinking skills. They stated that mathematics learning integrated with STEM should facilitate students' active engagement through higher-order thinking activities, rather than merely memorizing procedures.

Furthermore, the integration of STEM with vocational education, such as automotive engineering, is also supported by institutional studies stating that automotive education is part of STEM because it involves the application of science, technology, engineering, and mathematics in real work contexts (The Daily Automotive, 2025). Therefore, the success of STEM in the automotive context is directly related to how learning can develop students' critical thinking skills through meaningful and applicable activities.

The Realistic Mathematics Education (RME) approach was developed in the 1970s by Hans Freudenthal, who emphasized that mathematics is a human activity rather than merely a collection of formulas to be memorized (Freudenthal, 1971). Through RME, students are given opportunities to discover mathematical concepts through real-life contexts, allowing them to become more cognitively engaged in the learning process.

Furthermore, Realistic Mathematics Education (RME) has been empirically proven to improve students' mathematical critical thinking skills. Quantitative studies show that the implementation of RME can significantly improve mathematical critical thinking skills, including the ability to evaluate and make logical decisions regarding the problems

encountered, as shown by the results of RME implementation in experimental classes compared to control classes.

Other studies have also shown that the combination of Realistic Mathematics Education (RME) and the STEM approach is more effective in improving students' mathematical critical thinking skills in the era of Industrial Revolution 4.0 than conventional learning (Mirza & Aulia, 2019). This confirms that Realistic Mathematics Education (RME) is not only theoretically relevant but also has practical value when combined with STEM principles that require the contextualization of real-world problems in learning.

Critical thinking is an important factor in vocational education because students must be able to connect theory with practice in the workplace. Robert Sternberg (1999) stated that critical thinking involves mental processes used to solve problems, make decisions, and learn new concepts effectively. It is a key skill required by students to understand various real work phenomena in the automotive sector.

In addition to Sternberg, education scholars such as Burton (2004) and Ennis (2018) emphasize that critical thinking includes analytical, evaluative, reflective, and strategic abilities in solving complex problems, which cannot be acquired through mathematics teaching that is centered solely on procedural memorization. This becomes an important basis for redesigning mathematics learning in automotive vocational high schools by using an approach that provides greater space for critical thinking. Perkins further stated that critical thinking is the ability to collect, interpret, and evaluate information accurately and efficiently, which serves as a foundation for students when they are faced with real work situations in the automotive industry.

The integration of STEM in vocational education is viewed as a complementary strategy for preparing students to enter the workforce. Jie Feng and Haibo Hou (2023), in their review, stated that vocational education and training (VET) and STEM education are not only different, but also mutually reinforcing because both focus on skills needed in the workplace, especially when many vocational students are involved in STEM-related learning.

Another study stated that the STEM approach in mathematics learning directly improves students' mathematical critical and creative thinking skills and equips them with applicable problem-solving skills (Rahmawati et al., 2022). This finding supports the idea that STEM can facilitate students to think more deeply about problem solving through interactions among relevant disciplines.

In the context of vocational high schools, especially SMK Negeri 1 Pringgabaya, automotive engineering education is a vocational discipline that strongly requires a learning approach relevant to industrial needs. Real automotive problems, such as fuel consumption analysis, vehicle maintenance estimation, or component design, require not only technical skills but also analytical and critical thinking abilities to evaluate alternative solutions.

Research on the integration of RME and STEM in school settings confirms that when students are involved in real contexts through deliberately designed teaching modules, they are better able to develop substantial critical thinking skills, rather than merely memorizing mathematical procedures.

Based on the various scientific findings above, a STEM-based teaching module with a Realistic Mathematics Education (RME) approach is more than a pedagogical innovation. It is a theoretical and empirical response to the needs of vocational high school education in equipping students with critical thinking skills, real-world relevance, and work readiness in the era of Industrial Revolutions 4.0 and 5.0. This approach also supports vocational education that requires learning contexts to be more closely connected to the workplace.

Based on the discussion in this introduction, it can be concluded that STEM education, which integrates science, technology, engineering, and mathematics, is highly relevant for preparing vocational high school students to face the challenges of a rapidly developing and technology-intensive world of work. The STEM approach does not only focus on mastery of

academic content, but also on the development of generic skills such as critical thinking, problem solving, and collaboration, which are required by modern industries. However, the success of STEM implementation depends greatly on the quality of teaching at the school level, especially in vocational education contexts such as automotive engineering programs. One effective approach to improving students' critical thinking skills in mathematics learning is Realistic Mathematics Education (RME), which connects mathematical concepts with real-world contexts. By integrating STEM principles with RME, students can develop not only technical skills but also higher-order thinking skills that can be applied in real and dynamic work situations. This study aims to develop a STEM-based teaching module with a Realistic Mathematics Education (RME) approach, which is expected to improve the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program at SMK Negeri 1 Pringgabaya, East Lombok Regency. The implementation of this model is expected to serve as a solution to challenges in vocational education and help students become ready to meet the demands of the continuously developing automotive industry.

STEM education is highly relevant for preparing Automotive Engineering vocational high school students to face rapid changes in the technology-intensive automotive industry, including the need for critical thinking and problem-solving abilities. However, the benefits of STEM are strongly determined by the quality of its implementation, particularly in learning that is truly contextual and closely related to the world of work. The Realistic Mathematics Education (RME) approach is considered appropriate for bridging mathematics with real automotive situations through authentic contexts and mathematization processes, enabling students not only to understand concepts but also to analyze, evaluate, and make logical decisions. Therefore, the development of a STEM-based teaching module with an RME approach becomes an important strategy for improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program, while also strengthening the relevance of mathematics learning to industrial needs. The specific research question is as follows.

- How effective is a STEM-based teaching module with a Realistic Mathematics Education (RME) approach in improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program?

## LITERATURE REVIEW

### STEM Education and Critical Thinking Skills in the Context of Automotive Engineering Vocational Education

STEM education, which integrates science, technology, engineering, and mathematics, has become a major foundation for preparing students to face the dynamics of the world of work, which is increasingly influenced by technological advancement. Several studies have shown that the implementation of STEM in education can help students develop stronger critical thinking, creativity, and problem-solving skills, which are highly needed in today's labor market (Akcan et al., 2023; Swafford, 2018; Aunzo, 2024). However, along with these developments, many studies have also identified challenges in STEM implementation, particularly in vocational education contexts such as vocational high schools, where limitations in teacher readiness and facilities often become obstacles that reduce the effectiveness of this program (Villán-Vallejo et al., 2022). In the context of automotive engineering vocational education, STEM is expected not only to teach technical skills but also to develop analytical and critical thinking abilities needed to deal with more complex work situations, such as those required in operating electric and hybrid vehicles (Osatis & Asavanirandorn, 2022).

One aspect that is often overlooked in the implementation of STEM in vocational high schools is the development of students' critical thinking skills. According to Swafford (2018), effective STEM learning must include a deep understanding of the application of scientific

concepts in more open and less structured situations, allowing students to develop higher-order thinking skills. However, in practice, many vocational schools still focus on procedural learning and routine practices that tend to slow the development of students' critical thinking skills (Tsakeni, 2022). Therefore, to improve critical thinking skills in vocational contexts, particularly in automotive engineering programs, a more integrative learning approach based on real problems in the field is needed.

### **Realistic Mathematics Education (RME) and Its Implementation in Vocational Education**

One approach that can help improve critical thinking skills in mathematics learning at vocational high schools is Realistic Mathematics Education (RME). This approach was first developed by Hans Freudenthal in the 1970s with the aim of making mathematics more relevant and meaningful for students by connecting it directly with real-world contexts. According to Zakaria and Syamaun (2017), the main principle of RME is the use of realistic contexts that enable students to develop a better understanding of mathematical concepts through direct experience and mathematization processes. In the context of automotive engineering, for example, students can learn mathematics through calculations of vehicle fuel consumption, gear ratio analysis, or estimation of vehicle maintenance costs, all of which are highly relevant to the automotive industry (Bal & Kapucu, 2022).

Several studies have shown that RME can improve conceptual understanding, problem-solving ability, and positive attitudes toward mathematics (Fauzan et al., 2018; Suwanto et al., 2023; Nguyen et al., 2020). The implementation of RME enables students not only to solve mathematical problems but also to understand the reasoning behind problem solving and to develop the ability to critique and compare several alternative solutions (FitzSimons, 2014). However, the implementation of RME is not without challenges, such as the need for more time to facilitate a more open and discursive learning process and limitations in teachers' mastery of the material, which may hinder effective implementation (Rosvall et al., 2016; Edo & Tasik, 2019). Therefore, the implementation of RME in mathematics learning at vocational high schools, particularly in automotive engineering programs, requires a more holistic approach that does not rely solely on the use of real-world contexts, but also on discussion-based and reflective learning.

### **Critical Thinking Skills in STEM Mathematics Learning**

Critical thinking skills are among the main competencies that students must possess in the era of Industry 4.0. In the STEM context, critical thinking does not only involve the ability to analyze information in depth, but also the ability to interpret data, make analysis-based decisions, and develop solutions to complex problems that are often not fully structured (Morales-Doyle, 2017). In mathematics learning at vocational high schools, particularly in automotive engineering programs, students are often faced with more complex and less structured problems that require higher-order thinking skills. However, as stated by Butler (2024), current learning remains procedural, in which students are more often asked to solve routine problems without being given opportunities to explain their reasoning or interpret results in a broader context. This leads to a gap between the technical skills students master and the critical thinking abilities needed to solve more complex problems in the workplace.

A number of studies have shown that problem-based learning can improve students' critical thinking skills by giving them space to solve more open-ended problems that are directly related to the real world (Akmal et al., 2025; Ghafara et al., 2025). This approach also supports the development of students' analytical, evaluative, and reflective abilities in facing industrial challenges. However, to achieve significant improvement in critical thinking, this approach must be well designed and supported by teaching strategies that allow students to engage in discussion, ask questions, and develop strong arguments related to the solutions they choose (Fathoni, 2020).

### **Integration of STEM and RME in Automotive Engineering Vocational Education**

The integration of STEM in automotive engineering vocational education is becoming increasingly important given the rapid development of automotive technologies, such as electric vehicles and increasingly complex automation systems. Therefore, a learning approach is needed that not only teaches technical skills but also encourages students to develop the critical and analytical thinking abilities required to face dynamic and challenging work situations. The integration of RME with STEM is expected to create more relevant and contextual learning and to facilitate the development of students' critical thinking skills in the automotive field (Fauzan et al., 2018). In this context, RME can be used to facilitate students' understanding of mathematical concepts applied in technical calculations, while also providing opportunities for discussion and evaluation of various alternative solutions to problems encountered in automotive industry practice.

However, as stated by Siregar et al. (2022), successful implementation of RME in vocational education requires a shift in the teacher's role from merely being an instructor to becoming a facilitator who guides students to think critically and encourages more interactive discussions. As mentors, teachers must be able to help students connect mathematical concepts with the technical contexts they study, as well as facilitate deeper reflection and analysis of the solutions they choose (Rosvall et al., 2016). Thus, effective implementation of RME in automotive engineering vocational high schools does not depend only on the use of real-world contexts, but also on students' active engagement and teachers' deep pedagogical competence.

### **STEM Education and Realistic Mathematics Education in the Context of Automotive Engineering Vocational Education**

STEM education, which integrates science, technology, engineering, and mathematics, has increasingly been accepted as a crucial approach to prepare students for the challenging dynamics of the world of work. In vocational education, especially in automotive engineering programs, the implementation of STEM is expected not only to teach basic technical skills but also to develop critical thinking and analytical abilities needed to deal with complex problems in industry. According to Akcan et al. (2023), STEM integration in learning does not only improve technical abilities but also strengthens skills such as creativity and adaptability, which are very important in a technology-intensive labor market. Another study by Swafford (2018) revealed that STEM can improve graduates' work readiness by providing them with deeper skills in problem solving and critical thinking.

However, the implementation of STEM in vocational high school learning, especially in vocational education such as automotive engineering, often faces challenges related to implementation quality. One major issue is teacher readiness and the availability of facilities that support STEM-based learning. Swafford (2018) stated that although STEM has great potential to develop critical thinking skills, theoretical claims about its benefits are not always reflected in students' learning outcomes. Therefore, in-depth contextual evaluation of STEM implementation in vocational high schools is necessary to ensure that this learning strategy can succeed in accordance with industrial needs and workplace challenges.

Rothman and Sisman (2016) also highlighted the importance of connections between educational institutions and industry in developing STEM programs. Collaboration through internships, industry-based projects, or work-based learning can help connect the theory learned in classrooms with real practice in the field. This is highly relevant in vocational education contexts such as automotive engineering, where students can develop technical skills as well as critical thinking skills that will be very useful in dealing with various situations that are not fully structured, such as in the maintenance of electric vehicles and other modern automotive technologies (Haapala et al., 2023; Bloomberg, 2024). However, another issue that arises is unequal access to industry partners, which can reduce the quality of industry-based learning experiences.

Fauzan et al. (2018) argued that although vocational education has been recognized as important in preparing a skilled workforce, many vocational high school curricula, especially those focused on automotive engineering, still emphasize procedural skills and routine practice. Students are often trained to complete technical tasks without being given sufficient opportunities to develop critical thinking skills. Osatis and Asavanirandorn (2022) confirmed that technological changes in the automotive industry, including electric vehicles and automation systems, require technicians who are not only able to carry out procedures but also to analyze data, solve complex problems, and think systematically.

### **Realistic Mathematics Education (RME): Implementation and Benefits in Vocational Education**

Realistic Mathematics Education (RME) is an approach developed to make mathematics more meaningful and relevant to students' everyday lives. Zakaria and Syamaun (2017) explained that in RME, students are not only taught mathematical formulas but also how to apply mathematics in solving real-world problems. In the context of automotive engineering, for example, mathematics learning may include technical vehicle data analysis, fuel consumption calculations, and the design of more efficient vehicle maintenance systems. This approach focuses on the mathematization of real-world situations, enabling students to understand mathematical concepts in a more practical and applicable way (Bal & Kapucu, 2022).

Fauzan et al. (2018) showed that RME can improve students' conceptual understanding of mathematics and their attitudes toward mathematics, which is often perceived as difficult and abstract. By using contexts that are close to students' lives, RME is able to connect mathematical concepts with real situations, encouraging students to be more active and creative in finding solutions to the problems they face. Suwanto et al. (2023) added that RME also helps students develop critical thinking skills through discussion and reflection processes, which are important aspects in developing their analytical skills.

However, Edo and Tasik (2019) pointed out that implementing RME in practice does not always run smoothly. They noted that although RME is theoretically very useful for developing critical thinking skills, the greatest challenge lies in teacher readiness and teachers' roles in facilitating a more open and dialogic learning process. Without adequate training, teachers tend to implement only part of the RME principles, such as the use of contextual problems, without changing their role from instructors to active facilitators of discussion. As a result, RME implementation does not reach its full potential in improving students' critical thinking skills.

Rosvall et al. (2016) added that in vocational education contexts, especially in vocational high schools, the teacher's role in RME becomes highly important because teachers must be able to connect technical contexts with mathematical concepts and encourage students to explore and develop their own solutions. However, in many situations, pressure from curricula that focus more on content coverage and examination preparation may hinder teachers from implementing more open and reflective learning approaches. Therefore, the implementation of RME in mathematics learning in automotive engineering vocational high schools requires continuous support, both in terms of teacher training and curriculum planning that allows flexibility for consistently applying RME principles.

### **Implementation of STEM and RME in Automotive Engineering Vocational Education**

The implementation of STEM in automotive engineering vocational education has unique challenges and opportunities. Osatis and Asavanirandorn (2022) noted that the automotive world is undergoing major changes along with the development of electric vehicle technology and automation systems. Therefore, automotive engineering education programs must be able to adapt to these developments by introducing students to new technologies and teaching them to connect the knowledge gained in the classroom with practices encountered

in the workplace. Kurniawan et al. (2021) also emphasized the importance of a curriculum that is relevant to the needs of the automotive industry in improving the quality of vocational high school graduates' skills.

In this regard, RME can be an appropriate solution because it allows students to learn mathematics through authentic automotive contexts. Siregar et al. (2022) highlighted that by using examples of real situations, such as vehicle data analysis or maintenance cost calculations, students can develop mathematical skills that are more applicable and relevant to the industrial world. In other words, RME can help students understand mathematics in a broader context and one that is closer to technical needs in the field.

However, as noted by FitzSimons (2014), achieving optimal results in the implementation of RME in automotive engineering vocational education requires significant changes in teaching approaches and teacher roles. Teachers do not only function as instructors who deliver information, but also as facilitators who encourage discussion, support students in the problem-solving process, and help them connect mathematical concepts with field practice. Therefore, STEM-based teaching modules that integrate RME must consider the important role of teachers in the learning process and provide adequate training and support to transform procedural learning patterns into more problem-solving- and discussion-based learning.

It can be concluded that the integration of STEM in vocational education, especially in automotive engineering programs, can make a significant contribution to the development of students' critical thinking skills. However, to achieve optimal results, STEM implementation must be balanced with a relevant and contextual learning approach, such as Realistic Mathematics Education (RME). Realistic Mathematics Education (RME) enables students to learn mathematics through real-world contexts, which is highly important in vocational education oriented toward practical skills. Nevertheless, the implementation of Realistic Mathematics Education (RME) in automotive engineering education requires strong support, both in terms of teacher training and curriculum design that supports the development of critical thinking and problem-solving skills. Therefore, this study focuses on the implementation of a STEM-based teaching module with a Realistic Mathematics Education (RME) approach, which is expected to improve the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program at SMK Negeri 1 Pringgabaya, East Lombok Regency.

## **METHOD**

### **Research Design**

This study employed a mixed-methods approach with an explanatory sequential design. In this design, quantitative data collection and analysis were conducted first, followed by qualitative data collection to provide a deeper explanation of the quantitative results. This design was selected because the study did not only examine the improvement of students' critical thinking skills after the implementation of a STEM-based teaching module with a Realistic Mathematics Education (RME) approach, but also explored the learning context that supported or limited the implementation of the module in the Automotive Engineering Expertise Program.

The quantitative phase used a quasi-experimental design with a pretest-posttest control group design. A quasi-experimental design was used because the assignment of students into the experimental and control groups followed the existing administratively formed classes at the school; therefore, the researcher did not conduct individual randomization. The experimental group received instruction using a STEM-based mathematics teaching module with an RME approach, while the control group received expository instruction, as commonly implemented at the school. Both groups were given a pretest before the instruction and a posttest after the instruction to identify changes in students' critical thinking skills.

**Table 1.** Research design

Group	Pretest	Treatment	Posttest
Experimental	O <sub>1</sub>	STEM-based teaching module with an RME approach	O <sub>2</sub>
Control	O <sub>1</sub>	Expository instruction	O <sub>2</sub>

Note: O<sub>1</sub> refers to the initial test of critical thinking skills, while O<sub>2</sub> refers to the final test of critical thinking skills after the instructional treatment.

The qualitative phase was conducted after the instruction and quantitative data collection had been completed. Qualitative data were obtained through semi-structured interviews with mathematics teachers. The interviews were directed at obtaining information about students' characteristics, difficulties in learning geometry, the relevance of automotive contexts in mathematics learning, the use of media and technology, students' misconceptions, and recommendations for instructional development. The qualitative data were used to strengthen the interpretation of the quantitative findings and explain the factors that supported or limited STEM-based mathematics learning with an RME approach in developing students' critical thinking skills.

### Research Site and Participants

The study was conducted at SMK Negeri 1 Pringgabaya, East Lombok Regency, West Nusa Tenggara Province. The quantitative participants were eleventh-grade TSM students in the Automotive Engineering Expertise Program. In this study, TSM refers to Motorcycle Engineering classes that are administratively part of the Automotive Engineering Expertise Program. Thus, the term TSM does not replace the nomenclature of the Automotive Engineering Expertise Program, but indicates the class in which the study was conducted.

The total number of quantitative participants was 62 students, consisting of 31 students from class XI TSM.1 as the experimental group and 31 students from class XI TSM.2 as the control group. The experimental group consisted of 29 male students and 2 female students, while the control group consisted of 31 male students. This composition reflects the characteristics of classes in the Automotive Engineering Expertise Program, which are dominated by male students.

**Table 2.** Research participants

Group	Class	Program	N	Gender	Treatment
Experimental	XI TSM.1	Automotive Engineering	31	29 male students, 2 female students	STEM-based teaching module with an RME approach
Control	XI TSM.2	Automotive Engineering	31	31 male students	Expository instruction
Qualitative informants	Mathematics teachers	Automotive Engineering	2	Not focused on in the analysis	Semi-structured interviews

The qualitative participants consisted of two mathematics teachers who understood the characteristics of students in the Automotive Engineering Expertise Program and the teaching of circles, arcs, and tangent lines at SMK Negeri 1 Pringgabaya. The teachers were selected as informants because they had direct experience teaching mathematics to students in the automotive expertise field, understood students' learning difficulties, and were familiar with the need to contextualize mathematics content with vocational fields.

### Learning Treatment

The treatment in the experimental group consisted of the implementation of a STEM-based mathematics teaching module with an RME approach. The module was used for the topics of circles, arcs, central angles, inscribed angles, arc length, and tangent lines. The instruction was designed using automotive contexts that were close to students' daily lives and expertise field, such as motorcycle wheels, tires, rims, disc brakes, disc holes, gears or

sprockets, pulleys, tire contact with the road surface, and determining the safe distance of components near a disc brake.

The module was implemented in four meetings, each lasting  $2 \times 45$  minutes. The first meeting discussed circle elements, arcs, and central angles through the modeling of wheels or discs as circles. The second meeting discussed the relationship between central angles and inscribed angles using the context of hole positions on a disc or points on the circumference of a wheel. The third meeting discussed arc length and its application to the distance traveled by a wheel based on its angle of rotation. The fourth meeting discussed tangent lines and a STEM mini-project on determining the safe distance of components near a disc brake.

The learning stages in the experimental group followed the principles of RME, namely realistic context orientation, exploration and informal modeling, mathematization, discussion, concept reinforcement, application, and critical reflection. At the context orientation stage, students were presented with real problems related to automotive components. At the exploration and informal modeling stage, students created sketches, tables, or initial representations of the given problems. At the mathematization stage, students transformed informal models into more formal mathematical forms, such as the arc length formula or a right-triangle model for tangent lines. At the discussion stage, students compared strategies, provided reasoning, and critiqued solutions. At the reflection stage, students reviewed the reasonableness of their answers, the appropriateness of units, and the possible application of the results to automotive contexts.

In the control group, instruction was carried out using an expository approach. The teacher explained concepts, provided sample problems, and asked students to complete structured exercises. Automotive contexts were used as illustrations, but the instruction did not systematically follow the RME stages and did not emphasize modeling activities, open discussion, and critical reflection as implemented in the experimental group.

### Research Instruments

The quantitative instrument in this study was a written test administered as both the pretest and posttest. The test consisted of 20 items, namely 15 multiple-choice items and 5 open-ended questions. The multiple-choice items were used to measure students' mastery of basic concepts related to circles, arcs, central angles, inscribed angles, arc length, and tangent lines. Mastery of these basic concepts was positioned as the cognitive foundation required for critical thinking because students cannot analyze problems, choose strategies, provide reasoning, or evaluate the reasonableness of answers without adequate conceptual understanding. The multiple-choice score ranged from 0 to 15, with a score of 1 for each correct answer and 0 for each incorrect answer.

Open-ended questions numbered 16 to 20 were used to measure students' mathematical critical thinking skills in automotive contexts. These five open-ended questions assessed students' abilities to calculate the arc length of a wheel, explain the relationship between central angles and inscribed angles, reason about the properties of tangent lines, construct a Pythagorean model for tangent lines, and solve an automotive engineering case related to the placement of components near a disc brake. Each open-ended question was scored from 0 to 4, resulting in a maximum open-ended score of 20.

The scoring of the open-ended questions referred to an analytic rubric for critical thinking skills, which included the abilities to understand the problem, construct a mathematical model, provide reasoning, check the reasonableness of the result, and draw conclusions. A score of 4 was assigned when the answer showed a correct model, coherent solution steps, strong reasoning, accurate calculation, result checking, and a clear conclusion. A score of 3 was assigned when the model and solution steps were correct but still contained minor errors. A score of 2 was assigned when the answer showed partial understanding but the model or reasoning remained weak. A score of 1 was assigned when the student attempted

to answer but the response was not yet aligned with the main concept. A score of 0 was assigned when the student did not answer or when the answer was irrelevant.

The qualitative instrument was a semi-structured interview guide for mathematics teachers. The interview guide consisted of 30 questions covering the characteristics of students in the Automotive Engineering Expertise Program in learning mathematics, prerequisite geometry concepts, students' difficulties in understanding circles and tangent lines, the use of automotive contexts, instructional strategies, media and teaching aids, the use of technology, forms of assessment, and recommendations for learning that is more relevant to the needs of the Automotive Engineering Expertise Program.

### **Data Collection Procedure**

Data collection was carried out through several stages. The first stage was coordination with the school and mathematics teachers to determine the experimental and control classes, agree on the learning schedule, and prepare instructional materials and research instruments. At this stage, the researcher ensured that the content delivered to both groups covered the same scope, namely circles, arcs, central angles, inscribed angles, arc length, and tangent lines. The second stage was the administration of the pretest to the experimental and control groups. The pretest was given before the treatment to identify students' initial abilities, especially their mathematical critical thinking skills in solving problems contextualized within the automotive field. The third stage was the implementation of instruction. The experimental group participated in learning using the STEM-based teaching module with an RME approach over four meetings. The learning activities involved observing automotive contexts, mathematical modeling, group work, discussion, calculation, checking the reasonableness of results, presentation, and reflection. The control group participated in expository instruction through teacher explanation, sample problems, and structured exercises. The fourth stage was the administration of the posttest to both groups after the entire series of learning activities had been completed. The posttest used a form and content scope equivalent to the pretest to measure changes in students' abilities after instruction. The fifth stage was qualitative data collection through semi-structured interviews with two mathematics teachers. The interviews were conducted to obtain supporting information about students' characteristics, challenges in learning geometry, the relevance of automotive contexts, students' misconceptions, and teachers' views on mathematics learning connected to vocational fields.

### **Data Analysis Techniques**

Quantitative data were analyzed using descriptive statistics, categorization of critical thinking skills, gain and N-Gain calculations, assumption testing, and inferential statistical tests. The analysis was conducted using the total test score, which consisted of multiple-choice and open-ended scores. The multiple-choice score represented mastery of basic concepts as the cognitive foundation of critical thinking, while the open-ended score assessed students' abilities to understand problems, construct mathematical models, provide reasoning, check the reasonableness of results, and draw conclusions. Thus, the total score was considered a more comprehensive representation of students' mathematical critical thinking skills in automotive contexts.

The multiple-choice score ranged from 0 to 15, while the open-ended score ranged from 0 to 20. The total score was obtained by adding the multiple-choice score and the open-ended score, resulting in a maximum score of 35. The total score formula was the multiple-choice score plus the open-ended score.

The percentage of critical thinking skills was calculated based on the total score using the following formula:  $\text{Percentage} = (\text{Total score obtained} / 35) \times 100$ . The category of critical thinking skills was determined based on the percentage of the total score. The categories used are presented as follows.

**Table 3.** Categories of critical thinking skills

Percentage of Total Score	Category
81–100	Very critical
61–80	Critical
41–60	Moderately critical
21–40	Less critical
0–20	Not critical

The improvement of critical thinking skills was analyzed using gain and N-Gain. Gain was calculated as the difference between the posttest and pretest scores. N-Gain was used to determine students' relative improvement by considering the maximum possible improvement that could still be achieved. The formulas for gain and N-Gain are as follows:

$$\text{Gain} = \text{Posttest score} - \text{Pretest score}$$

$$\text{N-Gain} = (\text{Posttest score} - \text{Pretest score}) / (\text{Maximum score} - \text{Pretest score})$$

The maximum score used in the N-Gain calculation was 35 because the main analysis used the total test score. The N-Gain category was determined as follows: high if N-Gain  $\geq 0.70$ , moderate if  $0.30 \leq \text{N-Gain} < 0.70$ , and low if N-Gain  $< 0.30$ .

Before inferential testing, the data were examined through assumption tests. The normality test was conducted using the Shapiro-Wilk test because the number of students in each group was fewer than 50. The normality test was applied to the pretest, posttest, gain, and N-Gain scores in both the experimental and control groups. The homogeneity of variance test was conducted using Levene's Test to determine the equality of variance between the experimental and control groups. The results of the assumption tests served as the basis for selecting parametric or nonparametric statistical techniques.

Inferential analysis was conducted using paired-samples t-test, independent-samples t-test, and mixed-design ANOVA. The paired-samples t-test was used to examine differences between pretest and posttest scores within each group. This test indicated the significance of the improvement in critical thinking skills after instruction in both the experimental and control groups. The independent-samples t-test was used to examine differences in posttest, gain, and N-Gain scores between the experimental and control groups. This test indicated whether the improvement in students' critical thinking skills in the experimental group differed significantly from that in the control group.

Mixed-design ANOVA was used to examine the effect of measurement time, the effect of instructional group, and the interaction between measurement time and instructional group on students' critical thinking skills. The time factor consisted of pretest and posttest, while the group factor consisted of the experimental and control groups. The time  $\times$  group interaction was the main focus because it indicated whether the change in scores from pretest to posttest in the experimental group differed significantly from the change in scores in the control group.

When the data did not meet parametric assumptions, the analysis was continued using nonparametric tests. The Wilcoxon signed-rank test was used as an alternative to the paired-samples t-test to compare pretest and posttest scores within the same group. The Mann-Whitney U test was used as an alternative to the independent-samples t-test to compare posttest, gain, or N-Gain scores between the experimental and control groups.

In addition to statistical significance, this study calculated effect sizes to determine the strength of the treatment effect. Cohen's *d* was used to examine the magnitude of differences between two groups or changes between pretest and posttest scores. The interpretation of effect size was carried out by considering the educational context, so the findings were not viewed only in terms of statistical significance, but also in terms of the practical meaning of students' improvement in critical thinking skills.

Qualitative data from teacher interviews were analyzed using thematic analysis. The analysis was conducted through the stages of reading the interview results, identifying units of meaning, coding relevant responses, grouping codes into themes, and interpreting the relationship between qualitative themes and quantitative results. The themes included the characteristics and learning needs of automotive students, the suitability of content and prerequisite knowledge, the use of automotive contexts, instructional strategies, instructional media and technology, students' misconceptions, and recommendations for instructional development. The results of the thematic analysis were used to explain the factors that supported or limited the implementation of STEM-based mathematics learning with an RME approach in the Automotive Engineering Expertise Program.

### Research Ethics

The study was conducted after obtaining permission from the school and coordinating with the mathematics teachers involved in the instruction. Before data collection, students were informed about the purpose of the activity, the form of the test administered, and the use of data for academic research purposes. Students' identities were kept confidential by using student codes during data processing and reporting. The collected data were used only for research analysis and thesis writing. Interviews with teachers were conducted after obtaining the informants' consent, and the interview results were used in a limited manner to support the interpretation of the research findings.

## RESULTS

This study involved 62 eleventh-grade TSM students in the Automotive Engineering Expertise Program at SMK Negeri 1 Pringgabaya. The students were divided into two groups: 31 students from class XI TSM.1 as the experimental group and 31 students from class XI TSM.2 as the control group. The experimental group received instruction using a STEM-based mathematics teaching module with a Realistic Mathematics Education (RME) approach, while the control group received expository instruction. The experimental group consisted of 29 male students and 2 female students, whereas the control group consisted of 31 male students.

The learning process in the experimental group was conducted through automotive contexts related to motorcycle wheels, tires, rims, disc brakes, disc holes, gears or sprockets, pulleys, tire contact with the road, and determining the safe distance of components near a disc brake. The material taught included circles, arcs, central angles, inscribed angles, arc length, and tangent lines.

### Description of Pretest and Posttest Scores

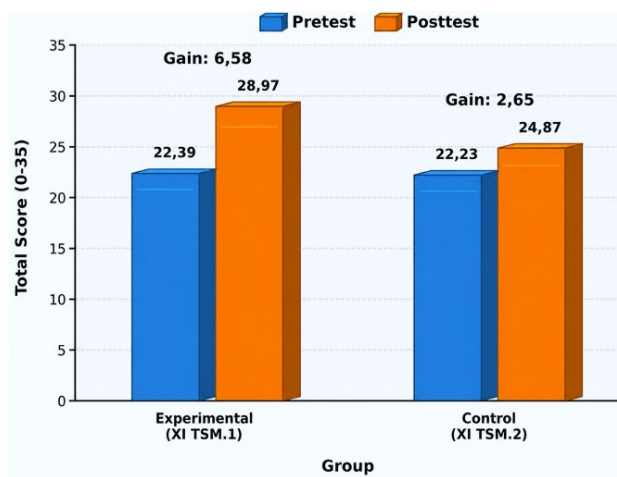
Quantitative data were obtained from a written test consisting of 15 multiple-choice items and 5 open-ended questions. The multiple-choice score ranged from 0 to 15, the open-ended score ranged from 0 to 20, and the total score ranged from 0 to 35. In this study, the total score was used as the main basis for analyzing critical thinking skills because it combined mastery of basic concepts and critical thinking ability as reflected in students' open-ended responses. The descriptive statistics of the pre- and posttest scores are presented in Table 4.

**Table 4.** Descriptive statistics of pretest and posttest scores

Score Component	Group	Pretest Mean	Pretest SD	Posttest Mean	Posttest SD
Multiple-choice	Experimental	7.74	0.73	12.32	0.91
	Control	7.48	1.09	9.06	0.89
Open-ended	Experimental	14.65	1.47	16.65	1.02
	Control	14.74	1.24	15.81	1.14
Total	Experimental	22.39	1.75	28.97	1.60
	Control	22.23	1.43	24.87	1.26

Based on Table 4, the initial abilities of the two groups were relatively balanced. The mean total pretest score of the experimental group was 22.39, while that of the control group was 22.23. After instruction, the mean total score of the experimental group increased to 28.97, whereas that of the control group increased to 24.87. The increase in the experimental group was greater than that in the control group. In the multiple-choice component, the experimental group increased from 7.74 to 12.32, while the control group increased from 7.48 to 9.06. In the open-ended component, the experimental group increased from 14.65 to 16.65, while the control group increased from 14.74 to 15.81. These findings indicate that STEM-based learning with an RME approach resulted in stronger improvement, both in mastery of basic concepts and in the ability to answer open-ended questions requiring reasoning.

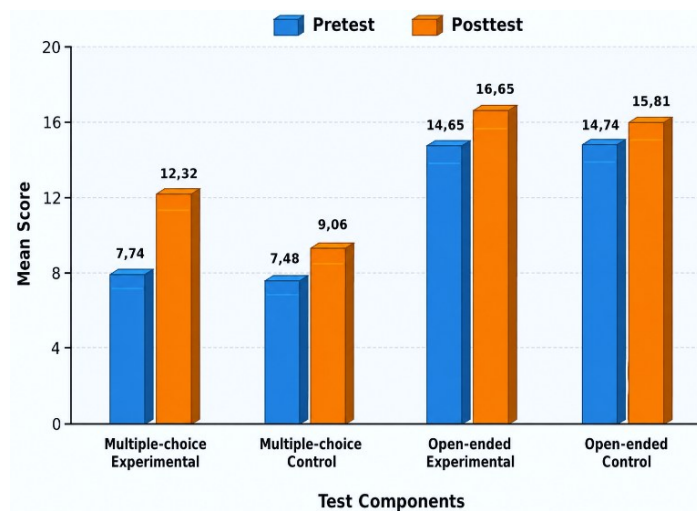
To clarify the difference in total score improvement between the experimental and control groups, the mean pretest and posttest scores are visualized in Figure 1.



**Figure 1.** Mean total pretest and posttest scores of the experimental and control groups

Based on Figure 1, both groups had almost the same initial position in the pretest. However, after the instructional treatment, the experimental group showed a greater increase in score than the control group. This pattern indicates that the difference in posttest results was not caused by a large difference in initial ability, but was related to the different instructional treatments received by the students.

In addition to the total score, the comparison of multiple-choice and open-ended scores is presented to examine changes in the two test components. The comparison is visualized in Figure 2.



**Figure 2.** Mean multiple-choice and open-ended scores in the pretest and posttest

Based on Figure 2, the increase in the multiple-choice score in the experimental group indicates stronger mastery of basic concepts. The increase in the open-ended score indicates that students also developed their ability to write reasoning, construct mathematical models, check the reasonableness of results, and connect their answers to automotive contexts. In the control group, improvement also occurred, but it was lower than in the experimental group, especially in the multiple-choice score and total score.

### Categories of Critical Thinking Skills

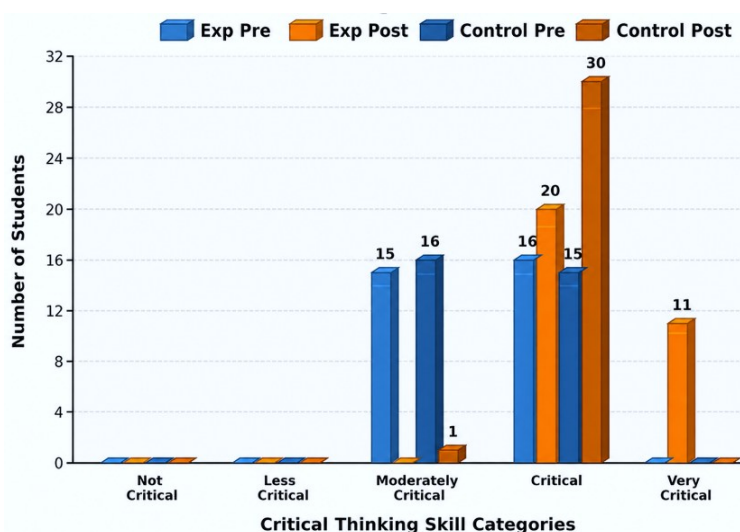
The categories of critical thinking skills were determined based on the percentage of the total score, namely the total score divided by the maximum score of 35 and then multiplied by 100. The categories used were not critical, less critical, moderately critical, critical, and very critical. The distribution of students' critical thinking skill categories in the pretest and posttest is presented in Table 5.

**Table 5.** Distribution of critical thinking skill categories based on total scores

Group	Test	Not Critical	Less Critical	Moderately Critical	Critical	Very Critical
Experimental	Pretest	0	0	15	16	0
	Posttest	0	0	0	20	11
Control	Pretest	0	0	16	15	0
	Posttest	0	0	1	30	0

Based on Table 5, during the pretest, the experimental group consisted of 15 students in the moderately critical category and 16 students in the critical category. After instruction, no students in the experimental group remained in the moderately critical category; 20 students were in the critical category and 11 students reached the very critical category. In the control group, the initial condition consisted of 16 students in the moderately critical category and 15 students in the critical category. After expository instruction, 1 student remained in the moderately critical category and 30 students were in the critical category. No students in the control group reached the very critical category in the posttest.

The changes in critical thinking skill categories are visualized in a bar chart in Figure 3 to make the category shifts in each group clearer.



**Figure 3.** Distribution of critical thinking skill categories in the pretest and posttest

Based on Figure 3, the most prominent change occurred in the experimental group, with 11 students reaching the very critical category after instruction. In the control group, improvement also occurred, but the shift was only from moderately critical to critical. Thus, the experimental group did not only experience an increase in mean scores, but also showed a qualitative shift in critical thinking to a higher category.

### Gain and N-Gain of Critical Thinking Skills

The improvement in critical thinking skills was analyzed using gain and N-Gain based on the total score. Gain shows the difference between posttest and pretest scores, while N-Gain shows the relative improvement compared with the maximum score that students could still achieve. The mean gain and N-Gain results are presented in Table 6.

**Table 6.** Mean gain and N-Gain of critical thinking skills

Group	N	Mean Gain	Gain SD	Mean N-Gain	N-Gain SD	N-Gain Category
Experimental	31	6.58	1.31	0.53	0.11	Moderate
Control	31	2.65	1.96	0.20	0.15	Low

Based on Table 6, the mean gain of the experimental group was 6.58, while that of the control group was 2.65. The mean N-Gain of the experimental group was 0.53 and was categorized as moderate, whereas the mean N-Gain of the control group was 0.20 and was categorized as low. This difference indicates that the improvement in students' critical thinking skills in the experimental group was higher than in the control group, both in terms of direct score difference and relative improvement.

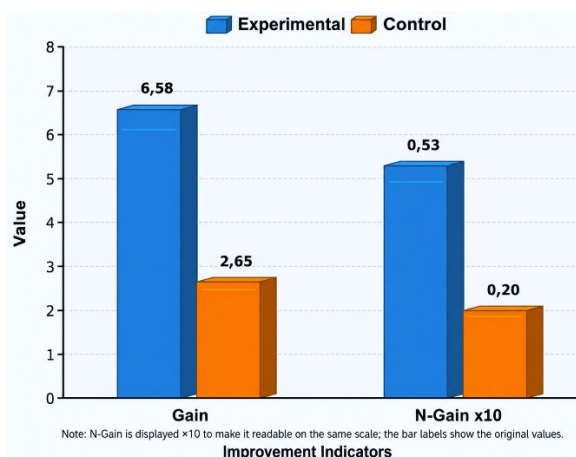
In addition to the mean N-Gain, the distribution of N-Gain categories was analyzed to identify the number of students who experienced low, moderate, and high improvement. The distribution of N-Gain categories is presented in Table 7.

**Table 7.** Distribution of N-Gain categories

Group	Low	Moderate	High
Experimental	0	28	3
Control	28	3	0

Based on Table 7, in the experimental group, 28 students were in the moderate N-Gain category and 3 students were in the high N-Gain category. No students in the experimental group were in the low N-Gain category. Conversely, in the control group, 28 students were in the low category, 3 students were in the moderate category, and no students reached the high category. These results strengthen the finding that the implementation of the STEM-based teaching module with an RME approach produced more consistent improvement among most students.

The difference in mean gain and N-Gain between the experimental and control groups is visualized in the bar chart in Figure 4.



**Figure 4.** Mean gain and N-Gain of the experimental and control groups

Based on Figure 4, the experimental group had higher mean gain and N-Gain scores than the control group. This pattern indicates that STEM-based learning with an RME approach not only improved students' final scores, but also produced greater relative growth from their initial ability.

### Assumption Testing for Statistical Analysis

Before inferential statistical tests were conducted, the data were examined through normality and homogeneity tests. The normality test was conducted using the Shapiro-Wilk test because the number of students in each group was fewer than 50. The normality test was applied to pretest, posttest, gain, and N-Gain scores in the experimental and control groups. The results of the normality test are presented in Table 8.

**Table 8.** Results of the Shapiro-Wilk normality test

Variable	Group	Shapiro-Wilk (W)	p
Total pretest	Experimental	0.834	<0.001
Total posttest	Experimental	0.735	<0.001
Gain	Experimental	0.872	0.002
N-Gain	Experimental	0.895	0.005
Total pretest	Control	0.752	<0.001
Total posttest	Control	0.735	<0.001
Gain	Control	0.809	<0.001
N-Gain	Control	0.782	<0.001

Based on Table 8, all variables had significance values lower than 0.05. This indicates that the pretest, posttest, gain, and N-Gain scores in both groups did not fully meet the assumption of normality. Therefore, the results of parametric tests were reported together with nonparametric tests to strengthen the interpretation.

The homogeneity of variance test was conducted using Levene's Test to determine whether the variances between the experimental and control groups were homogeneous. The results of the homogeneity test are presented in Table 9.

**Table 9.** Results of Levene's Test for homogeneity of variance

Variable	Levene Statistic	p	Interpretation
Total pretest	0.913	0.343	Homogeneous
Total posttest	5.769	0.019	Not homogeneous
Gain	3.864	0.054	Homogeneous
N-Gain	1.234	0.271	Homogeneous

Based on Table 9, the total pretest, gain, and N-Gain scores had significance values greater than 0.05, indicating that the variances of these three variables were homogeneous. The total posttest score had a significance value of 0.019, indicating that its variance was not homogeneous. Therefore, the comparison of total posttest scores between groups was analyzed by considering the Welch t-test results, while the other variables were analyzed using the independent-samples t-test under the assumption of homogeneous variances.

### Results of the Paired-Samples t-Test

The paired-samples t-test was used to examine differences between pretest and posttest scores within each group. This test indicated whether there was an improvement in critical thinking skills after instruction in both the experimental and control groups. The results of the paired-samples t-test are presented in Table 10.

**Table 10.** Results of the paired-samples t-test

Group	Pretest Mean	Posttest Mean	Mean Gain	t	df	p	Cohen's dz
Experimental	22.39	28.97	6.58	27.95	30	<0.001	5.02
Control	22.23	24.87	2.65	7.52	30	<0.001	1.35

Based on Table 10, the experimental group showed a significant increase between pretest and posttest scores,  $t(30) = 27.95$ ,  $p < 0.001$ . The mean score increased from 22.39 to 28.97, with a mean gain of 6.58. The Cohen's dz effect size of 5.02 indicated a very large improvement effect. In the control group, the paired-samples t-test also showed a significant

increase between pretest and posttest scores,  $t(30) = 7.52$ ,  $p < 0.001$ . The mean score increased from 22.23 to 24.87, with a mean gain of 2.65. The Cohen's  $d_z$  effect size of 1.35 indicated a large improvement effect, although it was still lower than that of the experimental group.

Because the normality test results showed that the data were not fully normally distributed, the paired-samples  $t$ -test results were strengthened using the Wilcoxon signed-rank test. The Wilcoxon results showed significant improvement in the experimental group,  $W = 0.00$ ,  $p < 0.001$ , and in the control group,  $W = 18.50$ ,  $p < 0.001$ . Thus, both groups experienced improvement after instruction, but the improvement in the experimental group was greater than that in the control group.

### Results of the Independent-Samples $t$ -Test

The independent-samples  $t$ -test was used to compare scores between the experimental and control groups. The variables compared included total pretest score, total posttest score, gain, and N-Gain. Because the homogeneity test showed that the variance of the total posttest score was not homogeneous, the comparison of total posttest scores used the Welch  $t$ -test results. The test results are presented in Table 11.

**Table 11.** Results of the independent-samples  $t$ -test

Variable	Exp. Mean	Control Mean	$t$	df	$p$	Cohen's $d$
Total pretest	22.39	22.23	0.40	60	0.692	0.10
Total posttest	28.97	24.87	11.20	56.81	<0.001	2.84
Gain	6.58	2.65	9.30	60	<0.001	2.36
N-Gain	0.53	0.20	9.64	60	<0.001	2.45

Based on Table 11, the total pretest scores of the experimental and control groups did not differ significantly,  $t(60) = 0.40$ ,  $p = 0.692$ . This indicates that the initial abilities of the two groups were relatively equivalent before the treatment. In the total posttest score, there was a significant difference between the experimental and control groups,  $t(56.81) = 11.20$ ,  $p < 0.001$ , with a Cohen's  $d$  effect size of 2.84. Significant differences were also found in gain,  $t(60) = 9.30$ ,  $p < 0.001$ , and N-Gain,  $t(60) = 9.64$ ,  $p < 0.001$ . The effect sizes for gain and N-Gain were 2.36 and 2.45, respectively, indicating very large differences between the two groups.

The Mann-Whitney  $U$  test was used as a supporting test because the data did not fully meet the normality assumption. The Mann-Whitney results showed no significant difference in pretest scores between the experimental and control groups,  $U = 492.00$ ,  $p = 0.867$ . Conversely, significant differences were found in posttest scores,  $U = 959.00$ ,  $p < 0.001$ , gain,  $U = 937.00$ ,  $p < 0.001$ , and N-Gain,  $U = 952.50$ ,  $p < 0.001$ . These results strengthen the finding that the improvement in critical thinking skills in the experimental group was higher than in the control group.

### Results of the Mixed-Design ANOVA

Mixed-design ANOVA was used to examine the effect of measurement time, the effect of instructional group, and the interaction between measurement time and instructional group on students' critical thinking skills. The time factor consisted of pretest and posttest, while the group factor consisted of the experimental and control groups. The results of the mixed-design ANOVA are presented in Table 12.

**Table 12.** Results of the mixed-design ANOVA

Source of Variation	F	df	$p$	$\eta_p^2$
Measurement time	475.01	1, 60	<0.001	0.888
Instructional group	43.48	1, 60	<0.001	0.420
Time $\times$ Group	86.43	1, 60	<0.001	0.590

Based on Table 12, there was a significant effect of measurement time on students' critical thinking skills,  $F(1,60) = 475.01$ ,  $p < 0.001$ , partial eta squared = 0.888. This indicates

that students' scores generally increased from pretest to posttest. The analysis also showed a significant effect of instructional group,  $F(1,60) = 43.48$ ,  $p < 0.001$ , partial eta squared = 0.420. The most important finding was the significant time  $\times$  group interaction,  $F(1,60) = 86.43$ ,  $p < 0.001$ , partial eta squared = 0.590. This interaction indicates that the change in scores from pretest to posttest in the experimental group differed significantly from the change in scores in the control group. In other words, the improvement in critical thinking skills among students who learned using the STEM-based teaching module with an RME approach was greater than that among students who received expository instruction.

### Results of Teacher Interviews

Qualitative data were obtained through semi-structured interviews with two mathematics teachers. The interview results were analyzed thematically and grouped into seven main themes. A summary of the themes and teacher interview findings is presented in Table 13.

**Table 13.** Summary of teacher interview findings

Theme	Focus of Findings	Summary of Results
- Characteristics and learning needs of automotive students	Student characteristics, geometry difficulties, and perceptions of the usefulness of the material	Students found it easier to understand mathematics when the material was connected to real objects such as tires, rims, disc brakes, gears, and turning radius. When the material was too abstract and consisted only of formulas, students' interest in learning decreased.
- Suitability of content, prerequisites, and learning sequence	Concept prerequisites and material sequence	The topics of circles and tangent lines required prerequisite concepts such as angles, triangles, ratios, basic algebra, and the Pythagorean Theorem. The appropriate sequence of material began with circle elements, circumference and area, central angles and inscribed angles, arcs and sectors, and then tangent lines.
- Learning resources and automotive contexts	Teaching resources and the use of vocational contexts	Teachers used textbooks, student worksheets, videos, GeoGebra, and contextual problems. The contexts frequently used included tires, rims, disc brakes, gears, sprockets, pulleys, and toothed wheels.
- Learning strategies and activities	Methods, activities, and context-based tasks	Discussions, structured exercises, demonstrations using teaching aids, measurement of real objects, and simple projects were considered helpful in enabling students to understand concepts more concretely.
- Learning media and technology	Teaching aids, GeoGebra, and constraints in technology use	The media used included compasses, rulers, protractors, circular cardboard models, images of automotive components, small tires, and mini wheels. GeoGebra helped visualize angles and tangent points, but its use was constrained by time, devices, and internet access.
- Students' misconceptions and difficulties	Conceptual errors and difficulties in solving problems	Students often confused radius and diameter, incorrectly used the formulas for circumference and area, selected the wrong angle in arc problems, and had difficulty sketching triangles in tangent-line problems.

Theme	Focus of Findings	Summary of Results
- Assessment and learning recommendations	Forms of assessment and development suggestions	Assessment should include written tests, practical drawing tasks, assessment of the discussion process, and interpretation of contexts. Learning was recommended to use more automotive contexts, real teaching aids, case-based problems, and visualization using GeoGebra or videos.

Based on Table 13, the teachers emphasized that mathematics learning in the Automotive Engineering Expertise Program was more easily accepted by students when it was connected to real-world contexts close to their vocational field. Contexts such as tires, rims, disc brakes, gears, sprockets, and pulleys helped students see the usefulness of the topics of circles, arcs, and tangent lines. The interview findings also showed that students still faced difficulties in geometry visualization, distinguishing between radius and diameter, selecting the appropriate angle in arc problems, and constructing triangle sketches in tangent-line problems. These findings support the importance of context-based learning, modeling, discussion, teaching aids, and reflection, as implemented in the STEM-based teaching module with an RME approach.

### Summary of Research Findings

The results showed that the experimental and control groups had relatively equivalent initial abilities. After instruction, the experimental group showed a greater increase in scores than the control group. The mean total score of the experimental group increased from 22.39 to 28.97, while that of the control group increased from 22.23 to 24.87. The mean N-Gain of the experimental group was 0.53, categorized as moderate, whereas that of the control group was 0.20, categorized as low.

The statistical test results strengthened these descriptive findings. The paired-samples t-test showed significant improvement in both groups, but the improvement in the experimental group was greater. The independent-samples t-test showed that the posttest, gain, and N-Gain scores of the experimental group differed significantly from those of the control group. The mixed-design ANOVA showed a significant time  $\times$  group interaction, meaning that the change in scores from pretest to posttest in the experimental group was greater than that in the control group. The qualitative findings from teacher interviews supported the quantitative results by showing that automotive contexts, the use of real objects, modeling, discussion, and reflection helped students understand mathematical concepts and develop critical thinking skills.

## DISCUSSION

The results of this study indicate that the implementation of a STEM-based teaching module with a Realistic Mathematics Education (RME) approach contributed positively to improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program. This finding is evident from the increase in total pretest-to-posttest scores in the experimental group, the shift in critical thinking skill categories to higher levels, the higher mean gain and N-Gain compared with the control group, and the statistical test results showing significant differences between the two groups. These findings are consistent with the view that STEM learning can help students develop critical thinking, problem-solving skills, creativity, and adaptability through active engagement in contextual and applicable problems (Akcan et al., 2023; Swafford, 2018; Nur Rarastika et al., 2025).

At the initial stage, the experimental and control groups had relatively equivalent abilities. The mean total pretest score of the experimental group was 22.39, while that of the control group was 22.23. This very small difference indicates that both groups began the learning process from almost the same initial condition. The independent-samples t-test on

the pretest scores also showed no significant difference between the two groups. Therefore, the higher improvement in the experimental group after instruction can be more reasonably attributed to the difference in instructional treatment received, rather than to differences in students' initial abilities.

After instruction, the experimental group showed a stronger increase in total scores than the control group. The mean total score of the experimental group increased from 22.39 to 28.97, while that of the control group increased from 22.23 to 24.87. The increase in the control group indicates that expository instruction can still help students understand certain materials, especially through teacher explanations, worked examples, and structured exercises. However, the improvement in the experimental group was greater because the learning process was not only centered on concept explanation, but also involved students in understanding real problems, constructing mathematical models, discussing strategies, providing reasoning, and reflecting on the reasonableness of their answers. This pattern is in line with the view that learning that provides space for problem solving, discussion, argumentation, and reflection is more supportive of critical thinking development than learning that focuses only on routine procedures (Sternberg, 1999; Ennis, 2018; Fathoni, 2020).

The increase in the multiple-choice score of the experimental group from 7.74 to 12.32 indicates stronger mastery of basic concepts. This finding is important because critical thinking skills do not stand apart from conceptual mastery. Students cannot analyze problems, choose strategies, or evaluate answers without understanding the basic concepts that serve as the foundation for problem solving. In this study, mastery of basic concepts related to circles, arcs, central angles, inscribed angles, arc length, and tangent lines served as the cognitive foundation for students to engage in further reasoning. This is consistent with the view of Ion Mierluș-Mazilu and Yilmaz (2023), who stated that mathematics learning in the STEM context needs to develop students' analytical and logical abilities as the core of critical thinking skills.

The increase in open-ended scores in the experimental group from 14.65 to 16.65 indicates a more explicit development of critical thinking ability. The open-ended questions required students not only to produce final answers, but also to demonstrate their thinking processes through solution steps, reasoning, mathematical models, result checking, and conclusions. The increase in open-ended scores suggests that students in the experimental group became better able to organize solutions systematically and connect mathematical concepts with automotive contexts. This finding is consistent with the principles of RME, which emphasize the use of real contexts and the process of mathematization from concrete situations toward formal mathematical forms (Freudenthal, 1971; Zakaria & Syamaun, 2017).

The shift in critical thinking skill categories further clarifies that the improvement in the experimental group was not merely numerical, but also qualitative. During the pretest, the experimental group consisted of 15 students in the moderately critical category and 16 students in the critical category. After instruction, no students remained in the moderately critical category; 20 students were in the critical category and 11 students reached the very critical category. In contrast, in the control group, the category improvement moved from moderately critical to critical, but no students reached the very critical category. This pattern indicates that STEM-based learning with an RME approach was more capable of encouraging some students to reach a higher level of critical thinking. This is in line with studies showing that RME can improve conceptual understanding, problem-solving ability, and mathematical critical thinking through students' engagement in real contexts and reflection on solutions (Fauzan et al., 2018; Suwanto et al., 2023; Mirza & Aulia, 2019).

This difference can be explained through the characteristics of the learning process implemented in the experimental group. The STEM-based teaching module with an RME approach used automotive contexts such as wheels, tires, disc brakes, gears, pulleys, and

tangent lines on vehicle components. These contexts were close to students' experiences and expertise field, so mathematics was not presented as an abstract concept detached from the real world. When students calculated arc length based on wheel rotation, analyzed angles on disc brakes, or determined the safe distance of components using a tangent-line model, they were not merely memorizing formulas, but using mathematics to understand and solve problems relevant to their vocational field. Such learning is consistent with the idea that vocational education needs to connect theoretical knowledge with workplace practice so that students develop more adaptive and applicable skills (FitzSimons, 2014; Morales-Doyle, 2017; O'Dea et al., 2024).

The connection between automotive contexts and mathematical concepts became one of the main strengths of the module. In the RME approach, context is not merely an addition to a problem, but the starting point for students to build understanding. Students were guided to observe situations, identify important information, create representations, develop informal models, and then formalize these models into mathematical formulas or procedures. This process provided space for students to connect concrete experiences with abstract concepts. This is in line with the principle of mathematization in RME, namely the process by which students organize real situations into increasingly formal and meaningful mathematical models (Freudenthal, 1971; Zakaria & Syamaun, 2017).

From the STEM perspective, the module encouraged integration among mathematics, technology, engineering, and simple scientific contexts in the automotive field. The mathematical element appeared in the use of concepts such as circles, arc length, angles, and tangent lines. The technological element appeared in the use of learning aids, component images, the possible use of GeoGebra, and visual representations. The engineering element appeared in activities involving component position analysis, safe distance determination, and a mini-project related to disc brakes. The scientific element appeared in discussions of wheel motion, tire contact with the road surface, and the relationship between component shape and mechanical function. This integration made learning more applicable and aligned with the characteristics of vocational education. This finding is consistent with the view that STEM integration can strengthen students' ability to understand real problems through relationships among relevant disciplines (Rahmawati et al., 2022; Villán-Vallejo et al., 2022; Feng & Hou, 2023).

The gain and N-Gain results strengthen the conclusion that the improvement in critical thinking skills in the experimental group was greater than in the control group. The mean gain of the experimental group was 6.58, while that of the control group was 2.65. The mean N-Gain of the experimental group was 0.53, categorized as moderate, whereas that of the control group was 0.20, categorized as low. These results indicate that students who learned using the STEM-RME module showed better relative improvement compared with the maximum possible improvement available to them. In other words, the improvement in the experimental group was not only greater in absolute terms, but also better when viewed in relation to the remaining room for improvement.

The distribution of N-Gain categories also showed a consistent pattern. In the experimental group, 28 students were in the moderate category and 3 students were in the high category, with no students in the low category. In the control group, 28 students were in the low category and only 3 students were in the moderate category. This difference indicates that the STEM-RME module did not only affect a few students, but produced relatively even improvement among most students. This finding strengthens the argument that context-based learning, modeling, and discussion enable students to build understanding and reasoning more actively than procedural learning (Edo & Tasik, 2019; Rosvall et al., 2016).

The paired-samples t-test results showed that both the experimental and control groups experienced significant improvement from pretest to posttest. This finding indicates that both forms of instruction had an effect on students' achievement. However, the magnitude of

improvement in the experimental group was much greater than that in the control group. Cohen's  $d_z$  in the experimental group was 5.02, while that in the control group was 1.35. This difference in effect size indicates that STEM-based learning with an RME approach had a stronger practical effect on improving students' critical thinking skills than expository instruction. This finding is consistent with studies stating that STEM-RME-based mathematics learning can be more effective in improving mathematical critical thinking ability than conventional learning (Mirza & Aulia, 2019; Suwanto et al., 2023).

The independent-samples t-test results also support this finding. There was no significant difference in pretest scores between the experimental and control groups, but significant differences were found in posttest, gain, and N-Gain scores. The effect sizes for the posttest, gain, and N-Gain were in the very large category. This strengthens the evidence that the improvement in students' critical thinking skills in the experimental group differed meaningfully from that in the control group. Because the normality test showed that the data were not fully normally distributed, the use of the Mann-Whitney U test as a supporting analysis was appropriate. The consistency between the nonparametric test results and the parametric test results strengthens the interpretation of the findings.

The most important finding from the inferential analysis was the mixed-design ANOVA result, which showed a significant time  $\times$  group interaction. This interaction indicates that the change in scores from pretest to posttest in the experimental group differed significantly from the change in scores in the control group. Thus, STEM-based learning with an RME approach was not only associated with increased scores over time, but also produced a greater pattern of improvement than expository instruction. The time  $\times$  group interaction is the most relevant evidence for the research design because it directly tests score changes in two groups from pretest to posttest.

These quantitative findings were supported by the results of teacher interviews. The teachers stated that students in the Automotive Engineering Expertise Program found it easier to understand mathematics when the material was connected to real objects such as tires, rims, disc brakes, gears, sprockets, pulleys, and toothed wheels. This statement is consistent with the RME principle that places real contexts as the starting point of mathematics learning. For vocational high school students, vocational contexts are not merely additional examples, but serve as a bridge for understanding the benefits and functions of mathematical concepts in the field they study. This is in line with the idea that vocational learning needs to connect academic content with work contexts so that learning becomes more meaningful and relevant for students (FitzSimons, 2014; Kurniawan et al., 2021; Osatis & Asavanirandom, 2022).

The teachers also revealed that students often experienced difficulties in visualizing geometry, distinguishing between radius and diameter, choosing the correct angle in arc problems, and constructing triangle sketches in tangent-line problems. These difficulties indicate that geometry learning cannot rely only on formula explanation. Students need visual representations, teaching aids, real objects, and modeling activities to understand relationships among geometric elements. The STEM-RME module addressed these needs through the use of automotive contexts, drawing or modeling activities, group discussions, and reflection. This view is consistent with studies emphasizing the importance of the teacher's role as a facilitator in helping students connect real contexts with mathematical concepts and encouraging them to construct their own solutions (Edo & Tasik, 2019; Rosvall et al., 2016; Siregar et al., 2022).

The interview results also showed that teachers viewed learning involving discussion, demonstrations with teaching aids, measurement of real objects, and simple projects as more effective than learning that only involved formula explanation. This finding strengthens the quantitative results because the module used in the experimental group emphasized these types of activities. During the discussion stage, students did not merely solve problems, but compared strategies and provided reasoning. During the reflection stage, students reviewed

the reasonableness of their answers and the appropriateness of units. These two activities are highly relevant to critical thinking skills because students were trained not to accept answers mechanically, but to assess the process and results of their solutions. Skills such as analyzing, evaluating, and making logical decisions are central to critical thinking (Sternberg, 1999; Burton, 2004; Ennis, 2018).

In the context of vocational education, the findings of this study have important implications. Mathematics learning in vocational high schools often faces challenges because students perceive mathematics as an abstract subject that is less related to their field of expertise. The STEM-based teaching module with an RME approach helped reduce the gap between school mathematics and vocational practice. Through automotive contexts, students could see that mathematics is used to understand shapes, motion, size, position, and relationships among vehicle components. Thus, mathematics learning does not only function to meet curriculum requirements, but also supports students' readiness to think when facing technical problems in the automotive field. This is relevant to the demands of automotive engineering education, which must prepare students to face technological developments, automation systems, and analytical needs in industry (Wagino, 2025; Osatis & Asavanirandom, 2022; Wannapiroon et al., 2021).

This finding is also consistent with the idea that critical thinking skills in vocational education need to be developed through contextual and problem-solving-oriented learning. Automotive engineering students do not only need procedural skills, but also the ability to analyze situations, choose strategies, evaluate alternatives, and make decisions based on logical reasoning. Expository instruction can help students understand basic procedures, but it tends to be more limited in providing space for modeling, argumentation, and reflection. In contrast, STEM-RME provides greater opportunities for students to build connections between mathematical concepts and real problems. This is consistent with the view that effective STEM learning needs to involve students in open-ended, less structured, and contextually relevant problems so that higher-order thinking skills can develop (Swafford, 2018; Morales-Doyle, 2017; Tsakeni, 2022).

Although the results indicate that the STEM-RME module was more effective than expository instruction, the interpretation of the findings still needs to be proportional. The mean N-Gain of the experimental group was in the moderate category, not the high category. This means that the module provided meaningful improvement, but did not yet enable all students to achieve maximum improvement. This is reasonable because the development of critical thinking skills requires time, habituation, and repeated learning experiences. Four instructional meetings were sufficient to show change, but not enough to form comprehensive and stable critical thinking skills in all students. This view is consistent with the literature stating that the implementation of RME and problem-based learning requires time, teacher readiness, and a consistent learning process to achieve optimal results (Edo & Tasik, 2019; Rosvall et al., 2016; Fathoni, 2020).

In addition, the improvement in the control group should also be understood fairly. The control group also experienced a significant increase from pretest to posttest. This indicates that expository instruction still has a function in helping students acquire initial understanding and solve routine problems. However, when the learning objective is directed toward critical thinking skills, expository instruction appears to be less powerful than learning that provides space for real contexts, exploration, modeling, discussion, and reflection. Therefore, the findings of this study should not be interpreted as meaning that expository instruction is completely ineffective, but rather that STEM-RME learning is more appropriate for improving critical thinking skills in the context of this study.

Pedagogically, the findings show that a STEM-based teaching module with an RME approach can serve as an alternative strategy for vocational mathematics learning. This module helps teachers connect mathematical concepts with the automotive world in a more

systematic way. Teachers do not merely use automotive contexts as illustrations, but make them part of the learning process. Students are invited to observe, model, calculate, interpret, and evaluate results. This process makes learning more active and provides space for students to construct their own understanding with teacher guidance. This is in line with the view that teachers in RME learning and vocational education need to act as facilitators who help students connect concepts with practice, rather than merely as transmitters of information (FitzSimons, 2014; Siregar et al., 2022).

Theoretically, this study strengthens the view that the integration of STEM and RME can support the development of critical thinking skills. STEM provides an interdisciplinary framework that connects mathematics with technology and engineering, while RME provides a pedagogical approach that places real contexts as the starting point of mathematization. The combination of the two produces learning that is not only contextual, but also requires students to think, reason, and reflect on solutions. In the context of automotive engineering, this integration becomes relevant because students learn mathematics through situations close to their field of expertise. This finding reinforces previous studies showing that the combination of STEM and RME can improve mathematical critical thinking ability more effectively than conventional learning (Mirza & Aulia, 2019; Rahmawati et al., 2022; Suwanto et al., 2023).

Thus, the findings of this study answer the main research question by showing that a STEM-based teaching module with a Realistic Mathematics Education approach is effective in improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program. This effectiveness is reflected in the increase in total scores, the shift in critical thinking categories, the higher mean gain and N-Gain, the significant differences between the experimental and control groups, and the support from qualitative teacher interview findings. The improvement occurred because the module combined the strengthening of basic concepts, the use of automotive contexts, mathematical modeling processes, discussion activities, and critical reflection relevant to the learning needs of vocational students.

## CONCLUSION

Based on the research findings, the STEM-based teaching module with a Realistic Mathematics Education (RME) approach was effective in improving the critical thinking skills of vocational high school students in the Automotive Engineering Expertise Program. This effectiveness was indicated by the higher increase in total pretest-to-posttest scores in the experimental group compared with the control group. The mean total score of the experimental group increased from 22.39 to 28.97, while that of the control group increased from 22.23 to 24.87. This finding indicates that instruction using the STEM-based teaching module with an RME approach made a stronger contribution to improving students' critical thinking skills than expository instruction.

In terms of test components, improvement in the experimental group occurred in both multiple-choice and open-ended scores. The increase in multiple-choice scores indicated stronger mastery of basic concepts as the cognitive foundation of critical thinking, while the increase in open-ended scores indicated the development of students' ability to understand problems, construct mathematical models, provide reasoning, check the reasonableness of results, and draw conclusions. Thus, the improvement in critical thinking skills in this study was reflected not only in final score achievement, but also in students' ability to connect mathematical concepts with automotive contexts.

The improvement in critical thinking skill categories also showed better results in the experimental group. Before instruction, students in the experimental group were in the moderately critical and critical categories. After instruction, no students remained in the moderately critical category; 20 students were in the critical category and 11 students reached the very critical category. In the control group, improvement occurred from moderately critical to critical, but no students reached the very critical category. This finding indicates

that the STEM-based teaching module with an RME approach not only improved students' scores, but also encouraged a shift in the quality of their critical thinking to a higher category.

The gain and N-Gain results further strengthened this conclusion. The mean gain of the experimental group was 6.58, while that of the control group was 2.65. The mean N-Gain of the experimental group was 0.53 and fell into the moderate category, whereas that of the control group was 0.20 and fell into the low category. The distribution of N-Gain categories also showed that most students in the experimental group were in the moderate category and a small number reached the high category, while most students in the control group were in the low category.

The statistical test results showed that the improvement in critical thinking skills in both the experimental and control groups was significant, but the improvement in the experimental group was greater. The independent-samples t-test showed significant differences in posttest, gain, and N-Gain scores between the experimental and control groups. The mixed-design ANOVA also showed a significant time  $\times$  group interaction, meaning that the change in scores from pretest to posttest in the experimental group differed significantly from the change in scores in the control group. Therefore, statistically, the STEM-based teaching module with an RME approach was proven to be more effective than expository instruction in improving students' critical thinking skills.

The qualitative findings from teacher interviews supported the quantitative results. The teachers emphasized that students in the Automotive Engineering Expertise Program found it easier to understand mathematics when the material was connected to real objects and vocational contexts, such as tires, rims, disc brakes, gears, sprockets, pulleys, and toothed wheels. Automotive contexts helped students see the relevance of mathematical concepts to their field of expertise. Therefore, the STEM-based teaching module with an RME approach can be regarded as a relevant instructional strategy for strengthening students' critical thinking skills in vocational mathematics learning.

## LIMITATIONS

This study has several limitations that should be considered when interpreting the findings. First, the study was conducted in only one school, namely SMK Negeri 1 Pringabaya, with eleventh-grade TSM students in the Automotive Engineering Expertise Program as participants. This condition means that the findings cannot yet be broadly generalized to all vocational high schools or other expertise programs without further testing in different contexts. In addition, the study used a quasi-experimental design with administratively formed classes, so the researcher did not randomly assign individual students to the experimental and control groups. Although the initial abilities of the two groups were relatively equivalent based on the pretest scores, the possibility of unmeasured class characteristics should still be taken into consideration.

Other limitations relate to the duration, content scope, and data sources. The instruction using the STEM-based teaching module with an RME approach was implemented over four meetings, so the findings reflect short-term effects rather than the long-term sustainability of critical thinking skills. The material used was also limited to circles, arcs, central angles, inscribed angles, arc length, and tangent lines, so the effectiveness of the module on other mathematics topics still needs to be examined. In addition, critical thinking skills were measured through a written test consisting of multiple-choice and open-ended items, while qualitative data were obtained from teacher interviews. Therefore, students' thinking processes during discussion, modeling, and reflection were not explored in greater depth through classroom observation or student interviews.

## RECOMMENDATIONS

Based on the findings, mathematics teachers in vocational high schools are encouraged to integrate vocational contexts into mathematics learning more systematically, especially in

topics that are directly related to students' fields of expertise. In the Automotive Engineering Expertise Program, contexts such as wheels, tires, rims, disc brakes, gears, sprockets, pulleys, and other vehicle components can be used as starting points for building conceptual understanding and critical thinking skills. Schools need to support the implementation of STEM-based learning with an RME approach by providing instructional media, teaching aids, contextual student worksheets, and visualization technologies such as GeoGebra. Future research is recommended to involve more schools, longer instructional duration, more varied mathematics topics, and additional data sources such as classroom observations, student interviews, and worksheet analysis so that the development of critical thinking skills can be understood more deeply.

#### ACKNOWLEDGMENT

The authors would like to thank the Master's Program in Science Education, Faculty of Science, Engineering, and Applied Sciences, Universitas Pendidikan Mandalika, for its academic support in the implementation and preparation of this thesis. The authors also express their gratitude to the supervisors for their guidance, feedback, and direction throughout the research and writing process. The authors extend their appreciation to the principal, mathematics teachers, and students of SMK Negeri 1 Pringgabaya, particularly class XI TSM in the Automotive Engineering Expertise Program, for providing the opportunity, support, and participation during the implementation of the study. The authors also thank all parties who contributed, directly or indirectly, to the data collection, data analysis, and preparation of this thesis manuscript.

#### FUNDING INFORMATION

This research did not receive external funding.

#### AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Kadir Alpan Alaydrus	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Sutarto		✓		✓	✓	✓			✓			✓		
Saiful Prayogi		✓		✓			✓	✓		✓		✓	✓	

#### CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

#### ETHICAL APPROVAL

The researchers meticulously followed ethical protocols throughout the research process, adhering to the principles outlined in the Declaration of Helsinki.

#### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy considerations of research participants.

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