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Multi-response optimization of biogasoline engine performance and exhaust emissions using the taguchi method

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Abstract

The application of high-ethanol bio gasoline in small spark-ignition (SI) engines offers a promising pathway to reduce exhaust emissions while supporting renewable fuel utilization in motorcycle transportation. However, ethanol-rich fuels create complex interactions between combustion characteristics, engine performance, and emission formation, requiring a comprehensive optimization strategy. This study aims to conduct multi-response optimization of a bio gasoline-fueled motorcycle SI engine by simultaneously evaluating exhaust emissions and performance characteristics. A Taguchi experimental design using an L_9 (3^4) orthogonal array was applied to investigate the effects of bio gasoline blend ratio (E70–E80), compression ratio, ignition timing, and spark plug type. The response variables include hydrocarbon (HC) and carbon monoxide (CO) emissions, as well as engine torque and power. Signal-to-noise ratio analysis and analysis of variance were employed to determine the significance of each control factor and to evaluate response robustness. The results show that emission characteristics are mainly influenced by fuel composition and ignition-related parameters, with bio gasoline type having the greatest contribution to HC reduction, while ignition timing and spark plug type significantly affect CO emissions. Conversely, engine performance responses are primarily controlled by compression ratio, indicating its dominant influence on combustion pressure development and thermal efficiency. The optimal parameter settings for minimizing emissions and maximizing performance are not identical, demonstrating a trade-off between these objectives. Therefore, a response-priority-based multi-response optimization approach was adopted, prioritizing emission reduction while maintaining acceptable engine performance. Experimental validation shows good agreement between predicted and observed results, confirming the reliability of the proposed optimization framework.

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Keywords

Taguchi method, Biogasoline, Compression ratio, Ignition timing, Spark plug type, Performance, Exhaust emissions

Introduction

The transportation sector remains one of the largest contributors to global energy consumption and urban air pollution, particularly in developing countries where motorcycles dominate daily mobility [1][2][3]. Small-displacement spark-ignition (SI) engines are widely used due to their simplicity and affordability; however, their high population density leads to significant cumulative exhaust emissions, especially carbon monoxide (CO) and unburned hydrocarbons (HC), which pose serious environmental and public health concerns [4][5][6]. Consequently, improving the energy efficiency of SI engines while simultaneously mitigating exhaust emissions has become a central challenge in sustainable transportation research.

From an energy and thermodynamic perspective, the efficiency of SI engines is fundamentally constrained by combustion irreversibility, heat losses, and incomplete fuel oxidation [7][8]. Classical thermodynamic theory indicates that increasing thermal efficiency requires improved combustion phasing, higher effective compression ratios, and optimized heat release rates [9]. However, these improvements often intensify in-cylinder temperature and pressure, which may adversely affect emission formation if combustion parameters are not carefully controlled [10]. This inherent coupling between energy efficiency, combustion characteristics, and pollutant formation highlights the necessity of integrated optimization strategies.

The use of renewable and oxygenated fuels has been extensively investigated as a pathway toward reducing fossil fuel dependency and improving combustion quality [11]. Ethanol-based fuels, including bio gasoline blends, are particularly attractive due to their renewable origin, high octane number, and intrinsic oxygen content [12], [13]. The presence of oxygen within ethanol molecules promotes more complete oxidation of hydrocarbons, thereby reducing HC and CO emissions under appropriate operating conditions [14], [15]. Moreover, ethanol exhibits a higher laminar flame speed and greater resistance to knock compared to conventional gasoline, which can enhance combustion stability and allow more aggressive engine tuning [16], [17].

Despite these advantages, ethanol combustion introduces additional complexity. The lower heating value of ethanol alters the energy release per unit mass of fuel, while its higher latent heat of vaporization affects mixture preparation and in-cylinder temperature evolution [18]. These effects significantly influence ignition delay, flame development, and combustion duration, particularly in small SI engines with limited thermal inertia [19], [20]. As a result, the benefits of bio gasoline cannot be fully realized without concurrent optimization of key engine parameters such as ignition timing, compression ratio, and ignition system characteristics.

Ignition timing is a critical control parameter governing combustion phasing and peak cylinder pressure location. Advancing ignition timing generally shifts the maximum pressure closer to top dead center (TDC), improving indicated work and engine performance [21]. However, excessive advance may increase heat transfer losses and combustion instability, leading to elevated emissions or efficiency penalties [22]. Similarly, increasing the compression ratio improves thermal efficiency according to fundamental thermodynamic principles, yet it also amplifies sensitivity to fuel properties and ignition characteristics, especially when high-ethanol blends are employed [23]. These interactions underscore the complex, non-linear relationship between performance enhancement and emission control.

To address such complexity, statistical and optimization-based approaches have been widely adopted. The Taguchi method has been extensively applied in engine research due to its robustness and ability to identify dominant control factors with a reduced experimental burden [24], [25]. Numerous studies have demonstrated the effectiveness of Taguchi-based optimization in improving engine performance or reducing emissions individually. To simultaneously consider multiple output responses, several multi-response optimization approaches have been developed. Grey Relational Analysis (GRA) converts multiple response values into a single grey relational grade through weighted normalization, allowing combined optimization of conflicting objectives. Desirability function methods, introduced by Derringer and Suich [26], transform each response into a dimensionless desirability score between zero and one, which are then aggregated into a composite desirability index. Principal Component Analysis (PCA) has also been applied to eliminate correlation among responses before aggregation. These techniques have been applied in engine research to balance trade-offs between performance and emission responses. More recently, multi-response optimization techniques often incorporating Grey Relational Analysis or desirability functions have been proposed to simultaneously consider multiple output responses.

Nevertheless, prior studies applying these multi-response frameworks have demonstrated varying degrees of success. For instance, [6] applied Taguchi-GRA to simultaneously optimize performance and emission characteristics of a diesel engine, achieving a composite improvement by assigning equal weights to all responses. Similarly, [3] employed a combined Taguchi and Grey relational analysis approach for spark-ignition engines, reporting trade-off conditions between NOx reduction and brake thermal efficiency. [13] Applied desirability-based optimization for hydrogen-enriched combustion systems, noting that mathematical aggregation alone could obscure physically meaningful response interactions. Despite these contributions, many existing studies treat multi-response optimization primarily as a mathematical fusion problem, with limited emphasis on engineering decision-making under realistic constraints. In practical engine applications, emission parameters are often subject to stricter regulatory limits, while performance characteristics must remain within acceptable operational margins. Therefore, a purely mathematical aggregation of responses may not adequately reflect real-world optimization priorities.

In this context, the present study proposes a response-priority-based multi-response optimization framework for a biogasoline-fueled motorcycle SI engine using the Taguchi method. Exhaust emissions (HC and CO) are treated as primary environmental objectives, while engine performance parameters (torque and power) are considered secondary operational objectives. This approach integrates thermodynamic principles, combustion characteristics of ethanol-based fuels, and practical engineering considerations to systematically balance energy efficiency, emission reduction, and performance output. By focusing on realistic trade-off management rather than purely mathematical response fusion, this study provides a practical and scalable optimization framework for renewable-fuel-powered SI engines.

Method

This study was designed to systematically investigate and optimize the exhaust emission and performance characteristics of a biogasoline-fueled spark-ignition (SI) engine using a response-priority-based multi-response optimization framework. The experimental methodology integrates controlled engine testing, Taguchi statistical design, robustness evaluation, and experimental verification to ensure that the obtained results are physically meaningful, statistically valid, and applicable to real operating conditions [3], [6], [24].

The experimental investigation was conducted on a single-cylinder, four-stroke SI motorcycle engine equipped with an electronic fuel injection (EFI) system. This engine configuration represents small-displacement engines commonly used in daily transportation, which have been widely discussed in internal combustion engine fundamentals literature [22]. All experiments were performed under controlled and repeatable operating conditions, while non-investigated parameters were maintained constant to minimize external disturbances.

The fuel used in this study was bio gasoline, prepared as volumetric blends of gasoline and bioethanol. Three ethanol blending ratios (E70, E75, and E80) were selected to investigate the combined influence of ethanol’s oxygenated molecular structure, high octane number, and altered thermophysical properties on combustion behavior and exhaust emissions in spark-ignition engines.

The control factors and their corresponding levels employed in this study are presented in Table 1. Four control factors bio gasoline type, compression ratio, ignition timing, and spark plug type were selected based on their strong physical relevance to combustion completeness, thermodynamic efficiency, and ignition stability in SI engines. The selection of these factors follows established practices in engine optimization studies and ensures that the investigated parameters remain within safe and practical operating limits.

A Taguchi-based experimental design was adopted to efficiently evaluate the effects of multiple control factors with a reduced number of experimental runs. The Taguchi method has been widely applied in internal combustion engine optimization studies due to its robustness and capability to identify dominant parameters under noisy experimental conditions. An L_9 (3^4) orthogonal array was employed to analyze four factors at three levels each is presented in Table 2.

Table 1. Control factors and level selection

Factor Code	Factor	Level Code		
		1	2	3
A	*Biogasoline*	E70	E75	E80
B	Compression Ratio	15,6:1	16,1 : 1	16,6 : 1
C	Ignition Degree	Std (6°)	+2°	+4°
D	Spark Plug	Nikel	Iridium	Platinum

Table 2. Orthogonal matrix L9(34)

Experiment	Factor			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The overall research methodology is illustrated in Figure 1, which outlines the systematic workflow adopted in this study. The framework begins with the identification of research objectives and selection of relevant control factors based on combustion and thermodynamic considerations. This is followed by the design of experiments using the Taguchi orthogonal array, experimental testing under controlled conditions, and data acquisition for both emission and performance responses.

Subsequently, the collected data are analyzed using average response analysis, signal-to-noise (S/N) ratio evaluation, and analysis of variance (ANOVA) to identify dominant factors and optimal parameter levels. The workflow concludes with experimental verification to validate the reliability and practical applicability of the optimized configurations. This structured framework ensures traceability between experimental design, data analysis, and final conclusions.

The response parameters were classified into exhaust emissions (HC and CO) and engine performance (torque and power). The smaller-the-better criterion was applied to emission responses, while the larger-the-better criterion was applied to performance responses, consistent with prior engine optimization studies balancing environmental impact and mechanical output.

The signal-to-noise (S/N) ratio formulation proposed by Taguchi was employed to evaluate response robustness against experimental variability. This approach enables identification of factor levels that optimize both response magnitude and stability. Analysis of variance (ANOVA) was conducted to statistically quantify the contribution of each control factor to response variability. This statistical approach is commonly adopted in Taguchi-based engine optimization studies to validate the significance of experimental results.

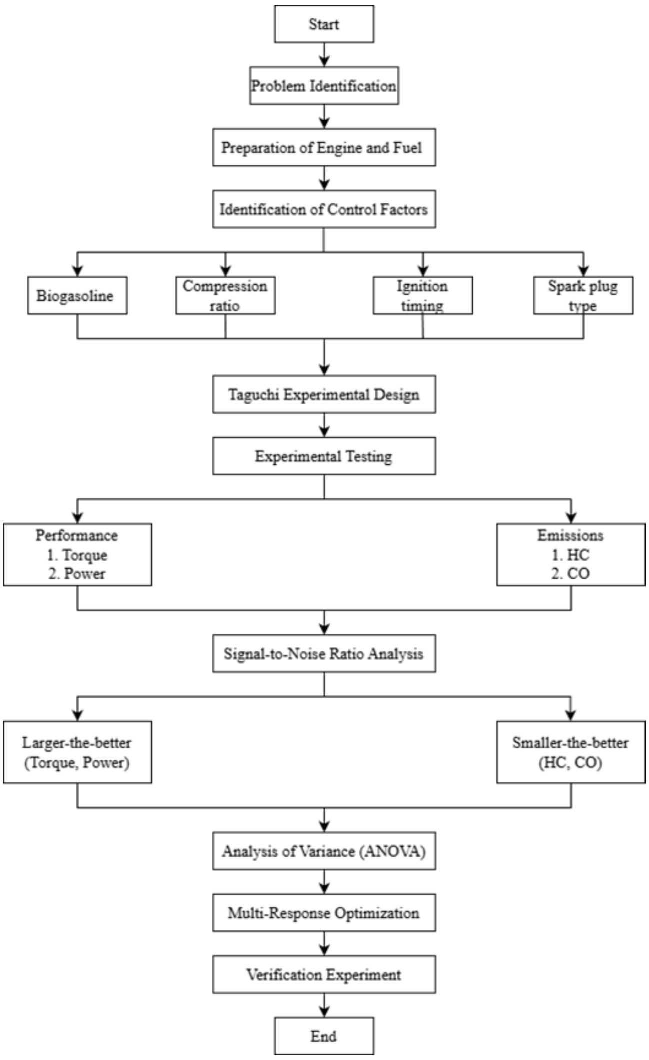

Figure 1. Research methodology flowchart

The response-priority-based multi-response optimization strategy adopted in this study prioritizes exhaust emission reduction while maintaining acceptable engine performance. This strategy aligns with recent multi-response optimization approaches applied in spark-ignition engine studies.

Experimental verification tests were conducted to evaluate the reliability of the optimized parameter combinations. Predicted responses were compared with experimentally measured values using percentage deviation and stability indicators. This verification approach confirms the practical applicability of the proposed optimization framework under real operating conditions.

Results

Average response

Table 3 summarizes the average hydrocarbon (HC) emission responses for each control factor level. Among the investigated parameters, bio gasoline type (Factor A) exhibits the largest variation in HC emissions, with a difference value of 3.96, indicating that fuel composition is the most influential factor governing HC formation in the tested spark-ignition engine. Ignition timing (Factor C) ranks second with a difference of 2.32, followed by spark plug type (Factor D) with a difference of 1.52, while compression ratio (Factor B) shows the smallest variation (Δ = 1.25). The difference value (Δ) represents the range between the maximum and minimum average response for each factor level and is used to indicate the relative influence of each control factor. Based on the smaller-the-better criterion applied to HC emissions, the optimal factor combination derived from the average response analysis is A2–B3–C1–D3.

Table 3. Table of average hydrocarbon response results

Experiment	**Factor**			
	A	**B**	**C**	**D**
Level 1	49.49	51.64	52.55	50.85
Level 2	53.45	50.80	51.71	51.28
Level 3	51.56	52.05	50.23	52.37
Max	53.45	52.05	52.55	52.37
Min	49.49	50.80	50.23	50.85
Diff	3.96	1.25	2.32	1.52
Rank	1	4	2	3
Optimal	A2	B3	C1	D3

The dominance of bio gasoline composition highlights the strong sensitivity of HC emissions to fuel chemical properties. Variations in ethanol content significantly affect the oxidation behavior of unburned hydrocarbons, leading to noticeable differences in average HC levels across the tested fuel blends. The results indicate a non-linear response, where the intermediate bio gasoline blend (A2) yields the lowest HC emission, suggesting a balance between enhanced oxygen availability and combustion stability under the tested operating conditions.

Ignition timing and spark plug type exhibit secondary but meaningful influences on HC emissions, reflecting the importance of ignition quality and combustion initiation consistency. Proper ignition timing (C1) supports more stable flame development and oxidation duration, while the optimal spark plug configuration (D3) contributes to improved ignition reliability. In contrast, the relatively small variation associated with compression ratio suggests that, under stable operating conditions, HC emissions are more strongly governed by fuel composition and ignition-related parameters than by compression effects alone. To further assess the robustness and statistical significance of these trends, signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) were subsequently performed, as discussed in the following subsections.

Table 4 presents the average carbon monoxide (CO) emission responses for each control factor level. Among the investigated parameters, spark plug type (Factor D) exhibits the most significant influence on CO emissions, as indicated by the largest difference value (Δ = 5.22). Ignition timing (Factor C) ranks second with a difference of 3.31, followed by compression ratio (Factor B) with a difference of 2.59, while bio gasoline type (Factor A) shows the smallest variation (Δ = 2.09). Based on the smaller-the-better criterion applied to CO emissions, the optimal parameter combination derived from the average response analysis is A2–B3–C2–D2.

Table 4. Table of average carbon monoxide response results

Experiment	**Factor**			
	A	**B**	**C**	**D**
Level 1	5.01	4.72	6.86	7.63
Level 2	7.1	5.84	7.17	7.73
Level 3	5.77	7.31	3.85	2.51
Max	7.1	7.31	7.17	7.73
Min	5.01	4.72	3.85	2.51
Diff	2.09	2.59	3.31	5.22
Rank	4	3	2	1
Optimal	A2	B3	C2	D2

The dominant influence of spark plug type highlights the importance of ignition quality and early flame development in governing CO formation. Differences in spark characteristics affect the stability and growth of the initial flame kernel, which in turn influence the extent of carbon oxidation during the combustion process. The results indicate that improved ignition reliability contributes to lower average CO emissions under the tested operating conditions.

Ignition timing also exhibits a pronounced effect on CO emissions by controlling combustion phasing and oxidation duration. Appropriate ignition advance ensures that sufficient temperature and residence time are available for the conversion of carbon monoxide to carbon dioxide. The relatively smaller but noticeable contributions of compression ratio and bio gasoline composition suggest that, while thermodynamic conditions and fuel oxygen content affect CO formation, ignition-related parameters play a more dominant role. To further evaluate the robustness and statistical significance of these trends, signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) were subsequently performed, as discussed in the following subsections.

Table 5. Table of average torque response results

Experiment	**Factor**			
	A	**B**	**C**	**D**
Level 1	74.88	75.73	73.93	74.34
Level 2	73.12	71.59	73.15	74.36
Level 3	73.93	74.61	74.86	73.24
Max	74.88	75.73	74.86	74.36
Min	73.12	71.59	73.15	73.24
Diff	1.76	4.14	1.71	1.12
Rank	2	1	3	4
Optimal	A1	B1	C3	D2

Table 5 presents the average torque response results for each control factor level. Among the investigated parameters, compression ratio (Factor B) exhibits the most dominant influence on engine torque, as indicated by the highest difference value (Δ = 4.14). This is followed by bio gasoline type (Factor A) with a difference of 1.76 and ignition timing (Factor C) with a difference of 1.71, while spark plug type (Factor D) shows the smallest variation (Δ = 1.12). Based on the larger-the-better criterion applied to torque, the optimal parameter combination obtained from the average response analysis is A1–B1–C3–D2.

The dominant contribution of compression ratio indicates that torque output is highly sensitive to compression-induced changes in in-cylinder pressure and effective expansion work. Higher compression ratios promote increased combustion pressure development, which directly enhances the mechanical work transferred to the crankshaft. This trend confirms that torque generation in the tested spark-ignition engine is primarily governed by thermodynamic factors rather than ignition hardware variations.

Bio gasoline composition and ignition timing exhibit secondary but comparable influences on torque response. Variations in fuel composition affect the rate of energy release, while ignition timing controls the phasing of peak combustion pressure relative to crank angle position. The relatively minor influence of spark plug type suggests that, under stable operating conditions, ignition reliability has a limited effect on steady-state torque once consistent combustion is achieved. The robustness and statistical relevance of these torque trends were further evaluated using S/N ratio analysis and ANOVA, as discussed in the subsequent subsections. Average power response results are shown in Table 6.

Table 6. Table of Average Power Response Results

Experiment	Factor			
	A	B	C	D
Level 1	72.22	72.66	70.86	71.26
Level 2	70.05	68.93	70.48	71.69
Level 3	70.86	71.54	71.78	70.16
Max	72.22	72.66	71.78	71.69
Min	70.05	68.93	70.48	70.16
Diff	2.17	3.73	1.3	1.53
Rank	2	1	4	3
Optimal	A1	B1	C3	D2

Table 6 summarizes the average power response results for each control factor level. Similar to the torque response, compression ratio (Factor B) exhibits the most significant influence on engine power, reflected by the highest difference value (Δ = 5.02). Ignition timing (Factor C) ranks second with a difference of 2.68, followed by biogasoline type (Factor A) with a difference of 2.21, while spark plug type (Factor D) shows the smallest variation (Δ = 1.35). According to the larger-the-better criterion, the optimal parameter combination for power output is A1–B1–C3–D2.

The strong dependence of power output on compression ratio reflects its role in improving overall thermal efficiency and indicated mean effective pressure. By increasing the pressure and temperature of the working mixture prior to combustion, a higher compression ratio enhances the total work produced per cycle, leading to increased power output under constant engine speed conditions. This explains the consistent dominance of Factor B across both torque and power responses.

Ignition timing and bio gasoline composition provide secondary contributions to power generation by influencing combustion phasing and fuel energy release characteristics, respectively. The similarity between the optimal parameter combinations for torque and power indicates a coherent performance trend, where favorable combustion pressure development also supports higher rotational output. The relatively small effect of spark plug type suggests diminishing returns in power enhancement once stable ignition conditions are maintained. The robustness of these power trends was subsequently assessed through S/N ratio analysis and ANOVA, as presented in the following sections.

Signal-to-Noise (S/N) ratio analysis

Figure 2 presents the signal-to-noise (S/N) ratio effect plot for hydrocarbon (HC) emissions based on the smaller-the-better criterion. The S/N analysis confirms the trends observed in the average response analysis, with bio gasoline type (Factor A) exhibiting the largest influence on response robustness. The highest S/N ratio is obtained at level A2, indicating that the intermediate ethanol blend provides not only the lowest average HC emissions but also the most stable emission behavior under experimental variability.

Ignition timing (Factor C) also demonstrates a noticeable effect on HC robustness, with the standard ignition setting (C1) yielding the highest S/N ratio. This suggests that appropriate combustion initiation timing is critical in minimizing cycle-to-cycle variations associated with incomplete combustion. Spark plug type (Factor D) shows a moderate influence on HC robustness, while compression ratio (Factor B) exhibits the smallest effect, reinforcing the conclusion that HC emissions are governed primarily by fuel chemistry and ignition-related parameters rather than compression-induced thermal effects alone.

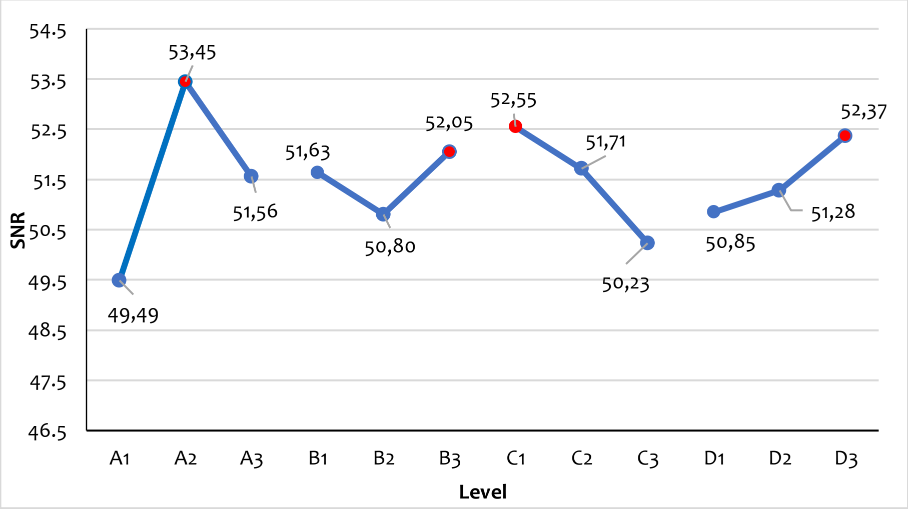

Figure 2. S/N Ratio Analysis for HC Emissions

The S/N ratio effect plot for carbon monoxide (CO) emissions is illustrated in Figure 3. Consistent with the average response results, spark plug type (Factor D) exhibits the most significant influence on CO robustness, with level D2 producing the highest S/N ratio. This indicates improved combustion stability and more consistent carbon oxidation when the optimal spark plug configuration is employed.

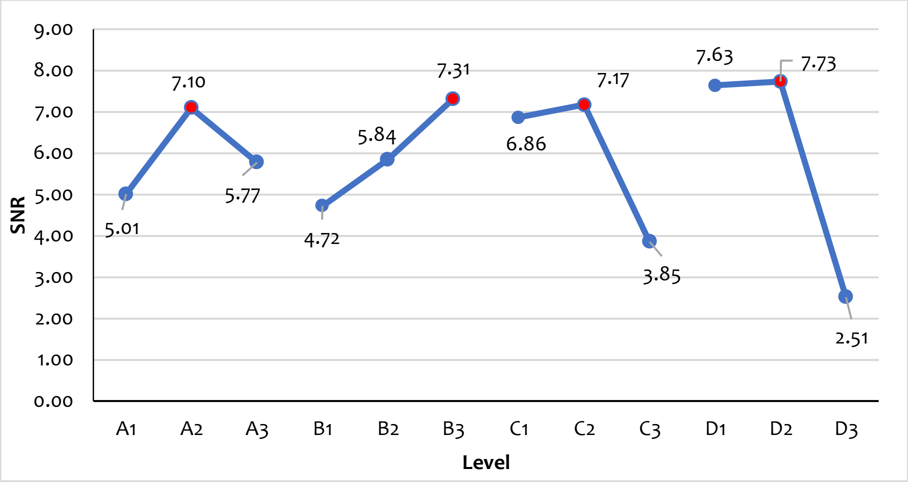

Figure 3. S/N Ratio analysis for CO emissions

Ignition timing (Factor C) ranks second in terms of influence on CO robustness, highlighting the importance of combustion phasing in ensuring sufficient oxidation duration for carbon monoxide. Compression ratio (Factor B) and biogasoline type (Factor A) show comparatively smaller effects on the S/N ratio, suggesting that while they affect average CO levels, their influence on emission stability is less dominant under the tested conditions.

Figure 4 shows the S/N ratio effect plot for engine torque using the larger-the-better criterion. Compression ratio (Factor B) clearly dominates torque robustness, with level B1 producing the highest S/N ratio. This result indicates that higher compression ratios not only increase average torque output but also improve the consistency of torque generation across repeated tests.

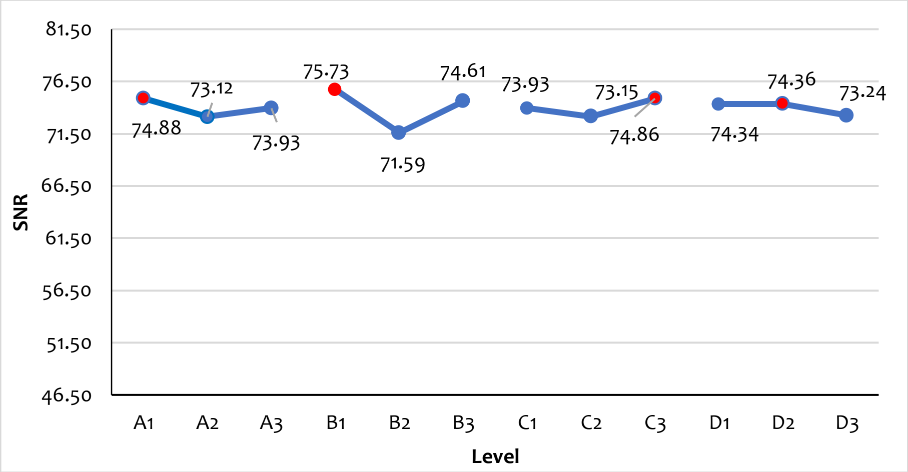

Figure 4. S/N Ratio analysis for torque

Ignition timing (Factor C) and bio gasoline type (Factor A) exhibit secondary but comparable influences on torque robustness, while spark plug type (Factor D) shows the smallest effect. These findings confirm that torque stability is primarily governed by thermodynamic parameters rather than ignition hardware variations.

The S/N ratio effect plot for engine power is presented in Figure 5. Similar to torque, compression ratio (Factor B) emerges as the most influential factor, with the highest S/N ratio observed at level B1. This indicates that power output stability is strongly linked to compression-induced improvements in combustion pressure and expansion work.

Ignition timing (Factor C) shows the second-largest contribution to power robustness, followed by bio gasoline type (Factor A). Spark plug type (Factor D) again exhibits the smallest effect, suggesting diminishing returns in power stability once reliable ignition is achieved.

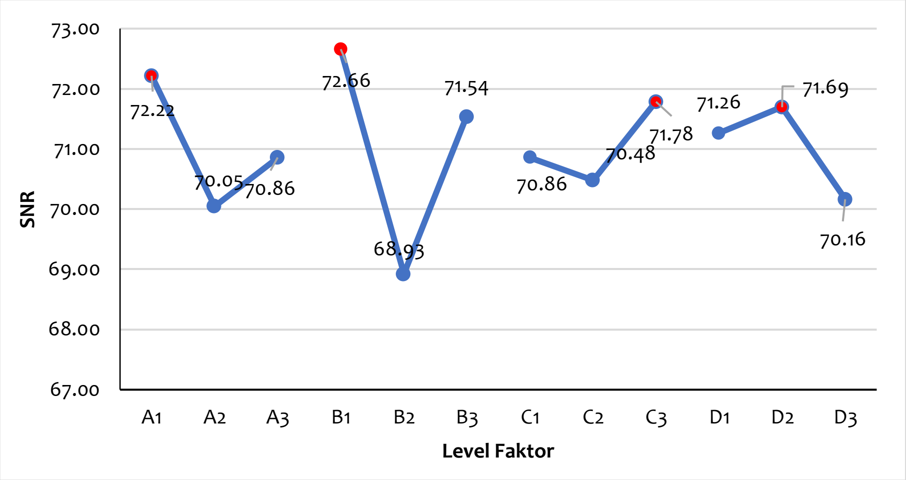

Figure 5. S/N Ratio analysis for power

Analysis of Variance (ANOVA)

The ANOVA results for HC, CO, torque, and power responses are summarized in Table 7,8,9,10. The ANOVA confirms the trends identified in both the average response and S/N ratio analyses.

Table 7. ANOVA hydrocarbon

Parameter	SS	Df	Ms	F Ratio	Ss'	Ratio %
A	23.52	2	11.76	4.39	18.16	47.9%
B	2.44	2	1.22	0.45	-	-
C	8.28	2	4.14	1.55	2.92	7.71%
D	3.68	2	1.84	0.69	-	-
Pooled e	10.72	4	2.68		21.43	56.52%
SSt	37.92	8	4.74		37.92	100%
Mean	23869.34	1				
SSTotal	23907.27	9				

For HC emissions (Table 8), biogasoline type (Factor A) exhibits the highest percentage contribution, statistically validating its dominant role in controlling hydrocarbon formation. Ignition timing (Factor C) contributes the second-largest share, while compression ratio (Factor B) shows the lowest contribution.

For CO emissions (Table 9), spark plug type (Factor D) is identified as the most significant factor, followed by ignition timing (Factor C). This confirms that CO formation is strongly governed by ignition quality and combustion phasing.

Table 8. ANOVA carbon monoxide

Parameter	SS	Df	Ms	F ratio	Ss'	Ratio %
A	6.72	2	3.36	0.8	-	-
B	10.12	2	5.06	1.2	-	-
C	20.12	2	10.06	2.39	20.12	22.25%
D	53.47	2	26.74	6.35	53.47	59.13%
Pooled e	16.84	4	4.21		16.84	18.62%
SSt	90.43	8			90.43	100%
Mean	319.64	1				
SSTotal	410.08	9				

Table 9. ANOVA torque

Parameter	SS	Df	Ms	F Ratio	Ss'	Ratio %
A	4.68	2	2.34	1.36	4.68	12.00%
B	27.54	2	13.77	8	27.54	70.45%
C	4.4	2	2.2	1.28	-	-
D	2.47	2	1.24	0.72	-	-
Pooled e	6.87	4	1.72		6.87	17.57%
SSt	39.09	8			39.09	100%
Mean	49254.05	1				
SSTotal	49293.14	9				

Table 10. ANOVA power

Parameter	SS	Df	Ms	F ratio	Ss'	Ratio %
A	7.2	2	3.6	2.24	7.2	20.20%
B	22.02	2	11.01	6.84	22.02	61.76%
C	2.7	2	1.35	0.84	-	-
D	3.73	2	1.86	1.16	-	-
Pooled e	6.43	4	1.61		6.53	18.32%
SSt	35.65	8			35.75	100%
Mean	45420.75	1				
SSTotal	45456.4	9				

In contrast, the ANOVA results for torque (Table 9) and power (Table 10) indicate that compression ratio (Factor B) contributes the largest proportion of response variance, underscoring its thermodynamic dominance in performance enhancement. The remaining factors show smaller but non-negligible contributions, reflecting secondary combustion and ignition effects.

Multi-response optimization strategy

The optimal parameter combinations derived from individual response analyses are not identical, reflecting an inherent trade-off between emission reduction and performance enhancement. Emission-oriented optimization favors intermediate ethanol content and conservative ignition settings, whereas performance-oriented optimization favors higher compression ratios and advanced ignition timing.

To address this trade-off, a response-priority-based multi-response optimization strategy was adopted. In this approach, exhaust emissions (HC and CO) were treated as primary objectives due to environmental and regulatory considerations, while torque and power were treated as secondary objectives. The final selected parameter combination represents a compromise solution that achieves substantial emission reduction while maintaining acceptable engine performance.

Discussion

This study demonstrates that optimization of a biogasoline-fueled spark-ignition engine cannot be effectively addressed through a single-response perspective, as exhaust emissions and engine performance are governed by different physical mechanisms and exhibit inherent trade-off behavior. By integrating average response analysis, signal-to-noise (S/N) ratio evaluation, analysis of variance (ANOVA), and experimental verification, this work provides a comprehensive multi-response interpretation that bridges combustion chemistry, thermodynamics, and practical engine operation.

The emission-related responses reveal that fuel composition and ignition-related parameters play a dominant role in determining combustion completeness and pollutant formation. The strong influence of bio gasoline type on hydrocarbon (HC) emissions highlights the importance of ethanol's oxygenated molecular structure in enhancing oxidation reactions. However, the non-linear trends observed across ethanol fractions indicate that increasing renewable fuel content alone does not guarantee optimal emission reduction. Instead, an intermediate ethanol blend provides a balance between oxygen availability, flame development, and mixture preparation, underscoring the coupled nature of chemical and thermal effects in small-displacement engines.

Carbon monoxide (CO) emissions are shown to be more sensitive to ignition quality and combustion phasing than to fuel composition alone. The dominance of spark plug type and ignition timing in both the S/N and ANOVA analyses confirms that stable early flame kernel formation and appropriate pressure development are critical for complete carbon oxidation. This finding emphasizes that emission mitigation strategies must consider ignition system characteristics in parallel with fuel substitution, particularly when high-ethanol blends are employed.

In contrast to emission behavior, engine performance responses are primarily governed by thermodynamic parameters. The compression ratio emerges as the most influential factor for both torque and power, reflecting its direct impact on thermal efficiency and effective expansion work. While bio gasoline composition and ignition timing contribute to performance enhancement, their effects are secondary to compression-induced pressure and temperature changes. These results align with classical engine thermodynamics, demonstrating that performance gains are closely tied to combustion phasing and in-cylinder energy conversion efficiency.

The divergence between optimal configurations for emission reduction and performance enhancement highlights the intrinsic trade-off in spark-ignition engine optimization. Emission-oriented settings prioritize combustion stability and oxidation completeness, whereas performance-oriented settings favour higher pressure development and expansion work. Rather than treating this divergence as a limitation, the present study addresses it through a response-priority-based multi-response optimization strategy. By assigning higher priority to environmental objectives (HC and CO reduction) while maintaining performance within acceptable operational margins, the proposed framework reflects realistic engineering decision-making under regulatory and practical constraints.

The robustness analysis further strengthens the validity of the proposed approach. The consistency between average response trends, S/N ratio behavior, ANOVA contributions, and experimental verification results confirms that the identified optimal parameter combinations are not only numerically favourable but also stable against experimental variability. The use of robustness-oriented metrics for emission responses and prediction accuracy metrics for performance responses is shown to be physically justified, given the noise-sensitive nature of emission measurements and the deterministic characteristics of torque and power.

Comparing the findings of this study with prior research provides important context for evaluating the contributions and positioning of the present work. Mishra et al. [6] reported an optimal compression ratio and fuel blend combination using Taguchi-GRA for diesel engines, noting a 12–15% improvement in brake thermal efficiency with simultaneous emission reduction. The present study similarly identifies compression ratio as the dominant factor for performance, while fuel composition governs HC emissions, consistent with these general trends. Yüce [3] reported that advancing ignition timing improved engine power but increased NOx emissions in gasoline engines, which aligns with the trade-off behavior observed here between emission-optimal and performance-optimal ignition settings. In terms of bio gasoline blends, Thakur et al. found that intermediate ethanol fractions (E20–E40) offered the best balance between HC reduction and power output in conventional gasoline engines. The present study extends this finding to higher ethanol concentrations (E70–E80), demonstrating that a non-linear optimum also exists at higher blend ratios, with E75 yielding the best emission performance. Compared to studies applying desirability functions or GRA with equal weighting, the response-priority-based framework proposed here offers a more transparent and physically grounded method for resolving multi-response conflicts under regulatory constraints. The experimental verification results, showing deviations within acceptable engineering tolerances, indicate that the proposed framework performs comparably to or better than conventional aggregation approaches in terms of prediction accuracy. The integration of physical interpretation, response prioritization, and experimental verification provides a practical and scalable optimization framework. The findings contribute to the development of cleaner and more efficient small-displacement engines and offer valuable insights for the broader implementation of high-ethanol bio gasoline fuels in sustainable transportation systems.

Limitations and implications

Despite these contributions, this study has several limitations that should be acknowledged. First, the experiments were conducted at a single engine speed condition, and the generalizability of the optimized parameter combinations to other speed ranges has not been validated. The interaction between engine load and the identified optimal settings warrants further investigation. Second, the orthogonal array design, while efficient, does not capture interaction effects between control factors, and some potentially important factor interactions may have been overlooked. Third, the study focuses on steady-state emission and performance responses, and transient behavior under real driving cycles is not addressed. Fourth, the bio gasoline blends were prepared under controlled laboratory conditions, and variability in bioethanol feedstock quality in commercial settings may affect reproducibility. In terms of practical implications, the findings suggest that small-displacement motorcycle engines can be effectively optimized for both emission compliance and performance retention through systematic parameter selection when operating on high-ethanol bio gasoline. The response-priority framework developed in this study is adaptable to other renewable fuel types and engine configurations, offering a transferable methodology for sustainable transportation applications. Future work should investigate multi-speed optimization, transient emissions testing, and the economic feasibility of implementing the recommended parameter combinations in commercially produced engines.

Conclusion

This study investigated the multi-response optimization of a small-displacement spark-ignition engine fueled with bio gasoline using a Taguchi-based experimental framework. The optimization simultaneously considered exhaust emission characteristics (hydrocarbon and carbon monoxide) and engine performance parameters (torque and power) to address the inherent trade-off between environmental impact and mechanical output.

The results demonstrate that exhaust emission behavior is primarily governed by fuel composition and ignition-related parameters. Bio gasoline type plays a dominant role in hydrocarbon emission reduction, while carbon monoxide emissions are strongly influenced by ignition timing and spark plug characteristics. These findings confirm that combustion completeness and oxidation stability are highly sensitive to ignition quality and fuel oxygen content in ethanol–gasoline blends.

In contrast, engine performance responses are mainly controlled by thermodynamic parameters. The compression ratio emerges as the most influential factor for both torque and power, highlighting its direct impact on thermal efficiency and effective expansion work. Ignition timing and bio gasoline composition contribute to performance enhancement but play secondary roles compared to compression-induced effects.

The optimization results reveal that the optimal parameter combinations for emission reduction and performance enhancement are not identical, confirming the presence of an intrinsic trade-off between these objectives. To address this challenge, a response-priority-based multi-response optimization strategy was adopted, in which emission parameters were treated as primary environmental objectives while engine performance was maintained within acceptable operational limits. This approach reflects realistic engineering decision-making under regulatory and practical constraints.

Experimental verification confirmed the reliability of the proposed optimization framework. The close agreement between predicted and experimental results, characterized by low percentage deviations and stable response behavior, demonstrates that the Taguchi-based method can provide robust and accurate guidance for parameter optimization in biogasoline-fueled engines.

Overall, this study contributes a practical and physically grounded multi-response optimization framework that integrates combustion chemistry, thermodynamics, and robustness analysis. The findings support the effective utilization of high-ethanol biogasoline fuels in small spark-ignition engines and provide a scalable methodology for balancing emission reduction and performance enhancement in sustainable transportation applications.

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References

1. I. Tiseo and M. Gonzalez, “Motorcycle growth and emission contribution in developing countries,” *Transportation Research Part D: Transport and Environment*, vol. 99, p. 102982, 2021.
2. Y. Zhang, X. Li, and H. Liu, “Urban air pollution from two-wheel vehicles: Emission characteristics and impacts,” *Atmospheric Environment*, vol. 223, p. 117278, 2020.
3. B. E. Yüce, “Multi-objective optimization of performance and emission characteristics of a spark-ignition engine using Taguchi and Grey relational analysis,” *Energy*, vol. 289, pp. 1–14, 2024.
4. M. Masi, S. Brusca, and R. Lanzafame, “Pollutant emissions from small-displacement motorcycles under real driving conditions,” *Energy Reports*, vol. 8, pp. 1231–1240, 2022.
5. International Energy Agency, *Transport Sector CO_2 Emissions*. Paris, France: IEA, 2021.
6. S. S. Mishra, S. Nayak, and A. K. Sahoo, “Overall performance investigation and optimization of engine characteristics using Taguchi–Grey relational analysis,” *ACS Omega*, vol. 7, no. 40, pp. 35774–35786, 2022.
7. S. E. Hosseini and M. A. Wahid, “Fossil fuel depletion and the role of alternative fuels in sustainable transportation,” *Renewable and Sustainable Energy Reviews*, vol. 123, p. 109738, 2020.
8. S. Verhelst and T. Wallner, “Hydrogen-fueled internal combustion engines,” *Progress in Energy and*

Combustion Science, vol. 72, pp. 1–30, 2019.

9. N. Saravanan, A. Nagarajan, and S. Narayanasamy, “Hydrogen enrichment effects on performance and emissions of spark-ignition engines,” *International Journal of Hydrogen Energy*, vol. 45, no. 21, pp. 11841–11854, 2020.
10. M. Kumar, A. Pandey, and R. S. Mishra, “Combustion characteristics of hydrogen-enriched gasoline engines,” *Fuel*, vol. 285, p. 119135, 2021.
11. A. Asnawi, “Effect of bioethanol–gasoline blends on the performance and emissions of a gasoline engine,” *Polimesin*, vol. 20, no. 2, pp. 85–92, 2022.
12. A. C. Yilmaz, E. Uludamar, and K. Aydin, “Effect of hydrogen addition on performance and exhaust emissions of a spark-ignition engine,” *Energy*, vol. 174, pp. 290–300, 2019.
13. B. K. Debnath, A. K. Saha, and S. Saha, “Hydrogen-enriched combustion as a pathway for emission reduction in gasoline engines,” *Journal of Cleaner Production*, vol. 333, p. 130102, 2022.
14. H. A. Alrazen, A. K. Ahmad, and M. S. Talib, “Hydrogen addition effects on combustion and emissions in gasoline engines,” *Energy Conversion and Management*, vol. 205, p. 112461, 2020.
15. K. Thakur, A. K. Kaviti, R. Mehra, and K. K. S. Mer, “Progress in performance analysis of ethanol–gasoline blends on spark ignition engines,” *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 324–340, 2017.
16. M. Ghazikhani, M. Hatami, and D. Ganji, “On-board hydrogen generation using water electrolysis for internal combustion engines,” *International Journal of Hydrogen Energy*, vol. 44, no. 25, pp. 12980–12989, 2019.
17. M. A. Saeed, M. A. Kalam, and H. H. Masjuki, “Performance evaluation of HHO-assisted internal combustion engines,” *Energy Reports*, vol. 7, pp. 4515–4524, 2021.
18. M. M. Rahman, K. Kadirgama, and R. Devarajan, “Electrolyzer power consumption and efficiency in hydrogen production systems,” *Renewable Energy*, vol. 182, pp. 1220–1230, 2022.
19. S. Khan, M. A. Hannan, and A. Mohamed, “PWM control strategies in electrochemical energy systems,” *Applied Energy*, vol. 262, p. 114569, 2020.
20. G. Najafi, B. Ghobadian, and T. Tavakoli, “Performance and exhaust emission analysis of a gasoline engine using variable ignition timing,” *Energy Conversion and Management*, vol. 105, pp. 120–130, 2015.
21. H. Zhang, Y. Wang, and L. Chen, “Power management strategies for on-board hydrogen electrolysis systems,” *Energy Conversion and Management*, vol. 278, p. 116626, 2023.
22. J. B. Heywood, *Internal Combustion Engine Fundamentals*, 2nd ed. New York, NY, USA: McGraw-Hill, 2019.