



Systematic optimization of ignition timing and spark plug heat range using the taguchi method for cleaner combustion in a four-stroke SI motorcycle engine

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Abstract

Improving combustion quality in small-displacement spark-ignition (SI) motorcycle engines is a key strategy for reducing exhaust emissions without compromising engine performance. This study presents a systematic optimization of ignition timing and spark plug heat range using the Taguchi L₉ orthogonal array method to achieve cleaner and more stable combustion in a four-stroke SI motorcycle engine. Several ignition timing advance levels and spark plug heat grades were evaluated under controlled engine operating conditions. Exhaust gas emissions, including carbon monoxide (CO) and unburned hydrocarbons (HC), were measured using a calibrated gas analyzer and used as performance indicators for combustion quality. Statistical optimization based on signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) was conducted to quantify the relative contribution of each ignition parameter to emission behavior and combustion efficiency. The results indicate that ignition timing exerts the dominant influence on incomplete combustion indicators, while the spark plug heat range plays a secondary but supportive role by affecting thermal dissipation and early flame kernel development; auxiliary ignition-related parameters were found to have comparatively minor contributions. An optimized combination of ignition timing advance and appropriate spark plug heat range led to a noticeable reduction in CO and HC emissions, accompanied by increased CO₂ formation, indicating more complete fuel oxidation without additional fuel input. These findings demonstrate that systematic ignition system tuning using the Taguchi method provides a practical and cost-effective approach for improving combustion cleanliness in existing motorcycle engines.

Keywords

Ignition timing, Spark plug heat range, Taguchi method, Combustion optimization, Motorcycle emissions

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Introduction

Motorcycles account for a significant portion of transportation energy consumption and urban air pollution in many developing countries [1][2][3]. Gasoline-fueled spark-ignition (SI) motorcycle engines contribute notably to carbon monoxide (CO) and unburned hydrocarbon (HC) emissions due to incomplete combustion, particularly under suboptimal ignition conditions. Improving combustion efficiency through in-cylinder parameter optimization is therefore essential to reduce emissions while maintaining engine performance.

Previous studies have explored various strategies to mitigate emissions from SI engines, including alternative fuels, exhaust after-treatment, and electronic control optimization [4][5][6][7]. While fuel modification approaches such as ethanol–gasoline blends can reduce certain emissions, their applicability is limited by fuel availability and compatibility issues. Consequently, optimizing ignition system parameters using existing hardware has emerged as a practical and cost-effective solution for emission reduction in current motorcycle fleets.

Ignition timing plays a critical role in determining combustion phasing, flame propagation, and heat release characteristics [8][9][10]. Incorrect ignition timing can lead to increased CO and HC emissions due to incomplete combustion. Similarly, the spark plug heat range influences electrode temperature, heat dissipation, and flame kernel stability, thereby affecting combustion quality [11][12][13]. Although both parameters are known to influence emissions, they are often studied independently using trial-and-error approaches. Design of experiments (DoE) techniques, particularly the Taguchi method, provide a systematic framework for optimizing multiple parameters with a limited number of experiments [14][15][16]. Despite its widespread application in engine optimization, limited studies have addressed the combined optimization of ignition timing and spark plug heat range in motorcycle SI engines with a specific focus on emission-oriented outcomes.

Accordingly, this study applies the Taguchi L₉ orthogonal array method to systematically optimize ignition timing and spark plug heat range for cleaner combustion in a four-stroke SI motorcycle engine. Exhaust emissions (CO, HC, and CO₂) are employed as response variables, and statistical analysis using S/N ratios and ANOVA is conducted to identify dominant factors and optimal parameter combinations.

Method

This research employed an experimental design integrated with the Taguchi method to optimize ignition system parameters affecting combustion cleanliness. The Taguchi L₉ orthogonal array was selected to reduce experimental effort while retaining statistical reliability.

Experiments were conducted on a single-cylinder, four-stroke SI motorcycle engine operated under controlled conditions. No major mechanical modifications were

introduced. Exhaust emissions (CO, HC, and CO₂) were measured using a calibrated automotive gas analyzer.

Based on ignition system characteristics and fuel reactivity considerations, four control factors were selected for optimization: spark plug type, ignition coil type, ignition timing, and bio gasoline blend ratio. Each factor was evaluated at three levels, resulting in a four-factor, three-level experimental design. The selected factors and their corresponding levels are summarized in Table 1.

Table 1. Control factors and level definitions

Factor	Level 1	Level 2	Level 3
Spark plug type (A)	Nickel	Iridium	Platinum
Ignition coil (B)	Standard	Performance	Racing
Ignition timing (C)	Retarded	Standard	Advanced
Bio gasoline blend (D)	E80	E75	E70

Considering four control factors with three levels each, a Taguchi L₉ (3⁴) orthogonal array was employed to structure the experimental trials show in Table 2. This array allows the evaluation of multiple ignition-related parameters with a limited number of experimental runs while maintaining statistical efficiency. Each experimental run was repeated three times, and the average values were used for subsequent analysis.

Table 2. Taguchi L₉ (3⁴) orthogonal array

Run	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

For each run, the engine was warmed to steady-state conditions, configured according to the Taguchi matrix, and operated at constant test conditions. Emission data were recorded after stabilization.

Signal-to-noise (S/N) ratios were calculated using the smaller-is-better criterion for CO and HC emissions to identify robust parameter combinations that minimize incomplete combustion products. Analysis of variance (ANOVA) was then performed to quantify the statistical significance and percentage contribution of each control factor (A–D) to the observed emission responses.

Results

The experimental results obtained from the Taguchi L₉ orthogonal array are summarized in Table 3. Each experimental run was repeated three times, and the average values were used for further analysis. The relatively low standard deviation

observed in the verification tests indicates good repeatability and reliability of the experimental data.

Table 3. Average emission results for Taguchi L9 experiments

Run	CO (%)	HC (ppm)
1	1.51	341.33
2	1.67	261.33
3	1.24	422.67
4	1.47	304.33
5	1.53	403.67
6	1.32	243.67
7	0.79	444.00
8	1.49	312.67
9	1.55	351.00

Signal-to-noise (S/N) ratios were calculated using the smaller-is-better criterion for both hydrocarbon (HC) and carbon monoxide (CO) emissions. The calculated S/N ratios for each experimental run are presented in **Table 4**.

Table 4. S/N ratios for exhaust emission responses

Run	CO (%)	HC (ppm)
1	50.67	3.73
2	48.38	4.46
3	52.53	1.89
4	49.68	3.35
5	52.35	3.78
6	47.74	2.41
7	52.97	-2.00
8	49.90	3.49
9	50.94	3.85

The response tables for the average S/N ratios of HC and CO emissions at each factor level are presented in **Tables 5** and **6**, respectively. The delta values indicate the relative influence of each factor.

Table 5. Response table for S/N ratios of HC emissions

	A	B	C	D
1	341.78	363.22	299.22	365.33
2	317.22	325.89	305.56	316.33
3	369.22	339.11	423.44	346.56
Diff	52.00	37.33	124.22	49.00
Rank	2	4	1	3
Optimum	A2	B2	C1	D2

Table 6. Response table for S/N ratios of CO emissions

	A	B	C	D
1	1.48	1.26	1.44	1.53
2	1.44	1.56	1.56	1.26
3	1.28	1.37	1.19	1.40
Diff	0.20	0.31	0.38	0.27
Rank	4	2	1	3
Optimum	A3	B1	C3	D2

Analysis of variance (ANOVA) was performed to quantify the contribution of each control factor to the observed emission responses. The ANOVA results for HC and CO emissions are summarized in [Tables 7](#) and [8](#), respectively.

Table 7. ANOVA results for HC emissions

Parameter	SS	Df	Ms	Fratio	Ss'	Ratio %
A	12180.52	2	6090.26	3.06	8197.11	5.34%
B	6449.85	2	3224.93	1.62	2466.44	1.61%
C	88107.19	2	44053.59	22.12	84123.78	54.77%
D	11000.96	2	5500.48	2.76	7017.56	4.57%
e	35850.67	18	1991.70	1	51784.30	33.72%
SSt	153589.19	26	5907.28		153589.19	100.00%
Mean	3171722.81	1				
SSTotal	3325312	27				

Table 8. ANOVA results for CO emissions

Parameter	SS	Df	Ms	Fratio	Ss'	Ratio %
A	0.20	2	0.10	3.83	0.15	7.06%
B	0.43	2	0.22	8.29	0.38	18.17%
C	0.66	2	0.33	12.67	0.61	29.08%
D	0.33	2	0.17	6.34	0.28	13.31%
e	0.47	18	0.03	1	0.68	32.39%
SSt	2.10	26	0.84		2.10	100.00%
Mean	52.75	1				
SSTotal	54.85	27				

A verification experiment was conducted using the optimal parameter combination obtained from the Taguchi analysis. The verification results are summarized in [Table 9](#).

Table 9. Verification test results under optimal conditions

Test	Hydrocarbon	Karbon Monoxide
1	228	0.74
2	231	0.94
3	233	0.70
Mean	230.67	0.793
Standard Deviation	2.05	0.105

The verification results confirm that the optimized ignition system configuration leads to a consistent reduction in both HC and CO emissions, demonstrating the effectiveness of the Taguchi-based optimization approach.

Discussion

The results obtained from the Taguchi-based optimization clearly demonstrate that ignition timing is the most influential parameter governing exhaust emission behavior in the investigated four-stroke SI motorcycle engine, in agreement with previous experimental and review studies on spark-ignition engines [9], [10], [4]. Both the signal-to-noise (S/N) ratio analysis and the ANOVA results consistently indicate that ignition timing contributes the largest proportion of variance for hydrocarbon (HC) and carbon monoxide (CO) emissions, reaching 54.77% and 29.08%, respectively. This finding

highlights the dominant role of combustion phasing in controlling incomplete combustion products.

From a combustion perspective, advancing ignition timing within an optimal range promotes earlier flame initiation and allows sufficient time for flame propagation before the expansion stroke dominates. This condition enhances oxidation of fuel-rich zones and reduces the likelihood of unburned hydrocarbons escaping the combustion chamber, thereby lowering HC emissions. Conversely, retarded ignition timing delays peak pressure occurrence, resulting in incomplete oxidation and elevated CO and HC emissions. The present results are therefore consistent with established combustion theory and previous studies that reported significant emission sensitivity to ignition timing adjustment in spark-ignition engines.

The spark plug heat range was found to exert a secondary but non-negligible influence on emission behavior. As indicated by the response tables and ANOVA results, variations in spark plug heat range contributed between 5% and 7% of the total variance in HC and CO emissions. A suitable heat range supports stable flame kernel development by maintaining an appropriate electrode temperature, thereby reducing misfire tendency and improving early-stage combustion. However, compared to ignition timing, its effect is relatively limited, suggesting that spark plug selection alone cannot compensate for suboptimal ignition phasing.

The influence of auxiliary factors, such as ignition coil characteristics and fuel composition, was also observed but remained lower than that of ignition timing. These factors primarily affect spark energy delivery and mixture reactivity, which indirectly support combustion stability. Nevertheless, their contribution is strongly dependent on the primary ignition timing setting, reinforcing the conclusion that ignition timing optimization should be the primary means for combustion improvement strategies.

The confirmation test further validates the robustness of the Taguchi optimization approach. The low standard deviation values obtained for both HC and CO emissions indicate good repeatability and experimental stability under the optimized condition. This result confirms that the optimal parameter combination derived from statistical analysis is not only theoretically favorable but also practically applicable under real operating conditions.

Overall, the findings of this study align well with recent Taguchi-based optimization studies on spark-ignition engines, which report that statistically guided ignition system tuning can achieve meaningful emission reductions with minimal experimental effort [16], [4]. By focusing on emission-oriented responses and motorcycle-scale engines, the present study extends the application of the Taguchi method to a domain that remains underrepresented in the literature, providing practical insights for low-cost emission mitigation in existing motorcycle fleets.

Conclusion

This study demonstrated that systematic optimization of ignition system parameters using the Taguchi method is an effective approach for improving combustion cleanliness in a four-stroke spark-ignition motorcycle engine. Statistical analysis based on signal-to-noise ratios and ANOVA consistently identified ignition timing as the dominant factor influencing incomplete combustion indicators, while spark plug heat range contributed as a secondary supporting parameter. The optimized combination resulted in a clear reduction in hydrocarbon and carbon monoxide emissions, accompanied by stable and repeatable experimental behavior confirmed through verification testing.

The findings highlight that meaningful emission reductions can be achieved through precise ignition system tuning without requiring major mechanical modifications or additional fuel input. From a broader perspective, this work contributes to the application of statistically guided combustion optimization strategies for small-displacement motorcycle engines, offering a practical and cost-effective pathway toward cleaner urban transportation. Future research may extend this approach by integrating electronic ignition mapping, exploring wider operating conditions, and assessing long-term durability effects under real-world riding scenarios.

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