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Optimizing copper catalytic converter designs for emission reduction in automatic motorcycles using grey relational analysis

Sudirman Rizki Ariyanto[1,*], Warju[1], Komarudin[2], Ata Syifa' Nugraha[2], Susi Tri Umaroh[1]
[1]Automotive Engineering Technology Study Program, State University of Surabaya, Surabaya 60231, Indonesia
[2]Department of Mechanical Engineering and Industries, Malang State University, Malang 65145, Indonesia
[3] Study Program of Mechanical Engineering , University of Billfath, Lamongan 62261, Indonesia
[*]Corresponding author: sudirmanariyanto@unesa.ac.id

Abstract

Vehicle emissions remain a major environmental challenge in urban areas, particularly in developing countries like Indonesia, where motorcycles dominate transportation. Automatic motorcycles pose specific emission control difficulties due to their engine characteristics. This study experimentally evaluates six copper-metallic catalytic converter designs installed on a 150cc automatic motorcycle under idle and 3000 rpm conditions. Exhaust emissions of Carbon Monoxide (CO) and Hydrocarbons (HC) were measured using a gas analyzer. Grey Relational Analysis (GRA) was employed to optimize the design parameters. The E3 design (curvature height: 4 mm, diameter: 54 mm, length: 100 mm) exhibited the best performance, reducing CO to 3.72% and HC to 539 ppm. Compared to standard designs, E3 improved emission reduction by 18–36%. These findings confirm that catalyst geometry significantly influences emission control and demonstrate the effectiveness of GRA in multi-parameter optimization. The results contribute to the development of efficient, affordable catalytic converters, supporting sustainable transportation and aligning with SDG 13 goals for climate action.

Keywords:
Catalytic converter design, emissions reduction, grey relational analysis, motorcycle emissions.

1 Introduction

Environmental sustainability is an urgent global challenge that requires collective efforts to address various environmental issues, including air pollution and greenhouse gas emissions. The 2030 Agenda for Sustainable Development Goals, adopted by the United Nations, outlines 17 SDGs, with Goal 13 specifically targeting climate action [1], [2]. One of the primary contributors to air pollution and climate change in many countries, including Indonesia, is the transportation sector, particularly emissions from motor vehicles such as motorcycles [3]. Motor vehicle emissions, particularly from motorcycles, are a significant source of air pollutants, including Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NOx), and particulate matter, all of which degrade air quality and pose significant risks to both environmental health and public well-being [4], [5].

Indonesia has witnessed a significant increase in the number of motor vehicles, especially motorcycles, over the past few decades [6]. Stable economic growth and urbanization have led to a surge in vehicle ownership, particularly automatic transmission motorcycles [7]. One of the key factors behind this increase in vehicle ownership is the inadequate public transportation infrastructure and the ease of acquiring personal vehicles [8]. However, the rapid rise in vehicles has exacerbated traffic congestion and emissions, worsening air quality and climate impacts [9]. Therefore, innovative solutions are required to reduce emissions from automatic transmission motorcycles and improve air quality overall in Indonesia.

Several studies have investigated the use of transition metal catalysts to reduce emissions from various types of vehicles. Research utilizing transition metal-based catalysts has shown promising results in reducing pollutants from vehicle exhaust gases. For example, Ingle et al. [10] found that catalytic converters coated with nanomaterials effectively reduced CO and HC emissions in gasoline-powered vehicles. Additionally, Udhayakumar et al. [11] reported that catalytic converters coated with zinc and vanadium significantly reduced NOx emissions in diesel engines. Research by Beobide et al. [12] demonstrated that copper-based catalysts are highly efficient in oxidizing CO and methane (CH_4). These catalysts use a CeO_2-ZrO_2 mixed oxide as a support, which enhances oxygen storage capacity and catalytic efficiency.

However, despite these advancements, critical gaps persist. Yakoumis [13] introduced copper-based catalysts combined with other metals such as palladium and rhodium. This catalyst showed performance that is on par with, or even better than, commercial catalysts, reducing the use of precious metals by up to 85%. Irawan et al. [14] explored the use of manganese as a supporting catalyst for copper in catalytic converters, with results indicating that manganese can significantly reduce CO emissions, especially when the number of catalyst cells is increased. Additionally, Dey & Mehta et al. [15] investigated the application of titanium oxide-based catalysts, resulting in significant reductions in greenhouse gas emissions. However, these studies predominantly focus on conventional vehicles or diesel engines, leaving a gap in tailored solutions for automatic motorcycles, a rapidly growing segment in Indonesia with distinct engine dynamics and emission profiles [16], [17].

This research resolves the identified gap through an innovative two-phase strategy. First, we conduct experimental optimization of copper metallic catalytic converter designs by systematically varying key parameters - curvature height, diameter, and length - to match the unique exhaust system requirements of automatic motorcycles. Second, we perform comprehensive performance evaluations under real-world operating conditions to simultaneously validate emission reduction (targeting HC, CO, and NOx) and ensure minimal backpressure impact on engine performance. This dual strategy ensures both technical efficacy and practical applicability for Indonesia's dominant motorcycle fleet.

The primary objective is to develop an efficient, low-cost catalytic converter specifically for automatic motorcycles, aligning with Indonesia's climate action priorities (SDG 13). By testing our hypothesis that copper-based catalysts with optimized geometry can significantly reduce emissions, we aim to provide actionable data for policymakers and manufacturers. This work not only addresses a technical gap but also supports Indonesia's transition to cleaner mobility, offering scalable solutions for similar emerging markets.

2 Methods

2.1 Engine

The experimental research was conducted using the Honda™ Vario 125 eSP motorcycle as the research object. The testing process was carried out using a device called an engine dynamometer, which was used to control the speed and load applied to the motorcycle (Fig. 1). Additionally, an exhaust gas analyzer probe was installed at the motorcycle's exhaust pipe to measure the amount of gas emitted during operation. During this process, data from the motorcycle's engine was recorded for further analysis. Detailed information regarding the engine specifications can be found in Table 1.

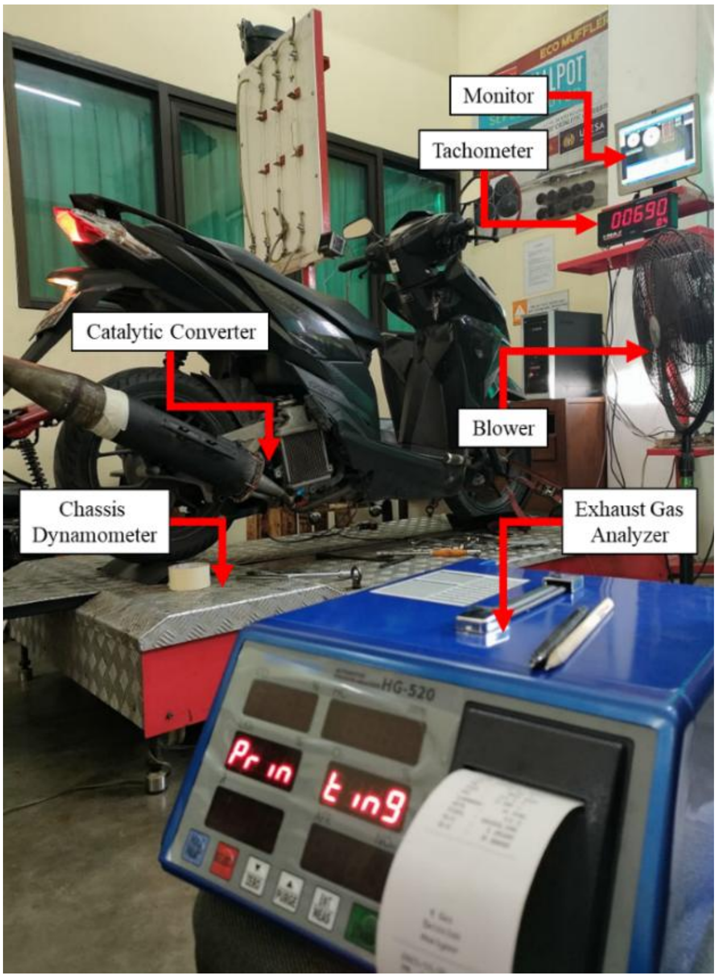

Fig. 1. Research Object

Table 1. Engine specifications

Specifications	Details
Engine Type	4-Stroke, SOHC, eSP, Liquid Cooling
Engine Displacement	124.8 cc
Bore and Stroke	52.4 x 57.9 mm
Maximum Power	10.9 HP at 8.500 rpm
Maximum Torque	10.8 Nm at 8.500 rpm

2.2 Catalyst Preparation and Testing

A copper metallic catalytic converter was developed using copper plates as the catalyst material, directly integrated into the exhaust pipe. Its primary function is to help reduce the number of harmful pollutants, such as HC and NOx, in the exhaust gases emitted by the engine. This process occurs primarily when the engine operates under lean mixture and stoichiometric conditions within a temperature range of 250–400°C [18], [19]. The catalyst was fabricated from commercially pure copper plates (99.9% Cu) shaped into corrugated structures without additional coatings or chemical treatments. This design leverages copper's inherent catalytic properties for oxidation-reduction reactions, as evidenced in prior studies [20], [21]. The specifications of the copper metallic catalytic converter used in this study are provided in Table 2, while its visualization is shown in Fig. 2. The parameters in Table 2 (e.g., curvature height, diameter, length) were optimized for exhaust flow efficiency and catalytic performance based on prior studies [20], [21] and engine design constraints.

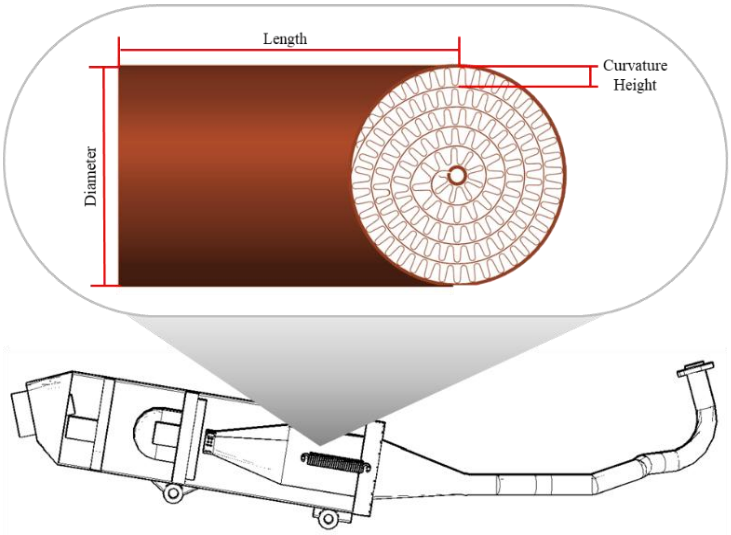

Fig. 2. Design Parameters of the Copper Metallic Catalytic Converter

This research involved six variations of the copper metallic catalytic converter design (E1-E6), which differ in the height of the catalyst curvatures, diameter, and length. In addition to these six designs, the study also included two additional comparative designs: a Standard without Catalyst (STD WC) and a standard exhaust with the standard Original Equipment Manufacturer (STD OEM).

2.3 Catalyst Testing

The exhaust gas emission testing was conducted to assess the performance of various copper metallic catalytic converter designs (E1-E6) across the engine speed range, from idle to 9000 RPM. To ensure that the data collected is consistent and reliable, exhaust emissions from automatic motorcycles were measured by the standards set by SNI 09-7118.3-2005 [22]. This was done to ensure that the results of the study possess high validity and reliability in evaluating exhaust gas emission reduction under various engine operating conditions.

4 Emissions Analysis

In this study, the Hesbon HG-520 instrument was used to measure various exhaust gas emission parameters, including total Hydrocarbons, Carbon Monoxide, carbon dioxide, and oxygen [23]. Another important parameter measured was the air-fuel ratio, denoted as λ, which refers to the comparison between the exhaust gas of the engine and its stoichiometric ratio [24], [25]. Additionally, the data generated was compared with the guidelines set by the Ministry of Environment Regulation No. 8 of 2023 [26], which establishes the exhaust emission limits for type L motor vehicles. The information obtained from these measurements will provide valuable insights into the exhaust emissions and the environmental viability of the motor vehicles under study.

Table 2. Copper Metallic Catalytic Converter Specifications

Catalyst	Code	Details		
		Curvature Height (mm)	Diameter (mm)	Length(mm)
Standard without Catalyst	STD WC	-	-	-
Standard Original Equipment Market	STD OEM	-	-	-
Experiment 1	E1	2	35	60
Experiment 2	E2	3	41	80
Experiment 3	E3	4	54	100
Experiment 4	E4	2	54	100
Experiment 5	E5	3	35	60
Experiment 6	E6	4	41	80

2.5 Grey Relational Analysis

Grey Relational Analysis (GRA) is a method used to transform large amounts of multi-objective data into a single value that reflects the degree of relationship or similarity between the compared objects [27]. The process begins with Step 1 (Data Normalization), where the initial dataset and reference data are normalized within a range of 0 to 1. This normalization is calculated using a formula (Eq. 1) that compares the original data values with the minimum and maximum values for each criterion, ensuring consistency across the dataset.

$$x_{ij}^{*} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{1}$$

The value x_{ij}^{*} represents the normalized value of alternative i for criterion j. x_{ij} is the initial value of alternative i for criterion j. min (x_j) is the minimum value of all data for criterion j, and max (x_j) is the maximum value of all data for criterion j.

In Step 2 (Calculate Grey Degree), the grey degree (GMj) is calculated by considering the differences between the reference data and the alternative data, alongside the maximum and minimum deviations from all data points (Eq. 2). These deviations are used to quantify how similar or different the alternatives are relative to the reference data. The formula takes into account a response coefficient (α), which typically ranges from 0 to 1, to adjust for the sensitivity to these differences [28].

$$GM_j = \frac{S_j^{-} + \alpha . S_j^{+}}{S_j^{-} + \alpha . S_j^{+} + \left|X_j^{0} - X_j^{*}\right|} \tag{2}$$

S_j^{-} represents the minimum deviation of X_j^{*}. S_j^{+} represents the maximum deviation of X_j^{*}. X_j^{0} is the reference data for criterion j. X_j^{*} is the normalized data for criterion j. α is the response coefficient to the difference between S_j^{+} dan S_j^{-}(typically ranging between 0-1).

Moving on to Step 3 (Grey Relational Degree), the grey degree for each criterion is used as a reference to calculate the grey relational degree (GRj) between each alternative and the reference data (Eq. 3). This step measures the degree of relational closeness between the alternatives and the reference, providing a comparative view of their performance on each criterion [29].

$$GR_j = \frac{\left|GM_j - GM_j^{0}\right|}{\max \left|GM_j - GM_j^{0}\right|} \tag{3}$$

GM_j represents the degree of fuzziness of the alternative data for criterion j. Meanwhile, GM_j^{0} represents the degree of fuzziness of the reference data for criterion j.

Finally, in Step 4 (Grey Relational Grade), the grey relational degrees for each criterion are aggregated to calculate the overall Grey Relational Grade (GRG). This aggregate value represents the overall relationship between the alternatives and the reference, providing a comprehensive evaluation based on multiple performance criteria. The GRG value is computed by summing the individual relational degrees across all criteria, resulting in a final score that reflects the overall quality of the alternative (Eq. 4).

$$GRA_i = \frac{1}{n}\sum_{j=1}^{n} GR_{ij} \tag{4}$$

GRA_i represents the aggregate GRA value for alternative i. n is the total number of criteria. GR_{ij} is the degree of relational fuzziness of alternative i for performance criterion j.

3 Results and discussion

3.1 Experiments and results

This study explores six variations of copper metallic catalytic converter designs, along with two additional designs for comparison, focusing on their impact on exhaust gas emissions. The experimental evaluation categorizes results into “Pass” (meeting emission standards) and “Fail” (exceeding limits) based on Minister of Environment Regulation No. 8 of 2023 [26], with copper-based catalysts as the key variable. The data in Table 3 illustrates the characteristics of the catalysts and their associated emissions.

Table 3. Experimental Results Metal Catalytic Converter Design

Catalyst	RPM	Threshold		Test Results		Category
		CO (%Vol)	HC(ppmVol)	CO (%Vol)	HC(ppmVol)	
STD WC	Idle	5.5	2200	5.82	949	Failed Emission Test
STD OEM				4.69	585	Passed Emission Test
E1				4.05	664	Passed Emission Test
E2				4.09	718	Passed Emission Test
E3				3.72	539	Passed Emission Test
E4				4.20	543	Passed Emission Test
E5				5.30	551	Passed Emission Test
E6				4.33	593	Passed Emission Test

The “Pass” category (E1-E6) achieved compliance due to optimized copper metallic catalytic properties: curvature height (2–4 mm), diameter (35–54 mm), and length (60–100 mm). These designs promoted sufficient exhaust gas-catalyst contact time, leveraging copper’s high redox activity for CO/HC conversion. Previous research confirms that diameter and length significantly affect CO conversion efficiency, with optimal dimensions maximizing gas-catalyst interaction [30]. For instance, E3 (4 mm curvature, 54 mm diameter, 100 mm length) showed the lowest emissions (CO: 3.72 %Vol, HC: 539 ppmVol), attributed to its larger surface area and balanced flow dynamics. Its folded-plate geometric design (curvature height 4 mm) aligns with findings from Lapisa et al.[31], which demonstrated that such designs enhance HC and CO reduction by improving flow distribution.

In contrast, the “Fail” category (STD WC, STD OEM, E5) exceeded limits because of suboptimal copper catalyst geometry e.g., E5’s high CO (5.30 %Vol) resulted from its narrow diameter (35 mm) and shorter length (60 mm), restricting reaction efficiency. Corroborates [30], where smaller diameters/lengths reduced CO conversion due to insufficient residence time. Notably, STD WC/OEM failed despite being manufacturer standards, as their non-copper designs lacked the tunable redox properties of copper-based catalysts, which are proven to outperform conventional materials in CO/HC reduction [32].

The performance gap between passed/failed designs underscores copper’s structure-dependent catalytic behaviour. Warju et al. [33] and Deng et al. [34] support these findings, noting that copper’s coordination environment and morphology dictate emission reduction efficacy. Further, [35] highlights that copper's morphology (e.g., particle size, surface area) directly impacts selectivity and efficiency, explaining why E3's larger dimensions (higher surface area) outperformed E5's compact design. Pan et al. [36] and Laskar et al. [37] further validate that material choice and geometric precision are critical for compliance.

The strict "Fail" categorization (if either CO or HC exceeds limits) highlights the non-negotiable need for holistic design optimization. Shoffan et al. [38] and Kim et al. [39] emphasize this, showing how copper catalyst dimensions directly impact emission outcomes. Thus, E3's success demonstrates that taller curvature (4 mm), wider diameter (54 mm), and extended length (100 mm) synergistically enhance copper's catalytic activity, further boosted by secondary metals as noted in [32], making it the most effective design.

3.2 Optimal parameter selection using grey relational analysis

This study strengthens the analysis of the calculation using the GRA Method. This step was taken to ensure that the best design could be identified from six variations of the copper metallic catalytic converter designs, along with two additional (standard) designs used as comparisons. Detailed results of the calculations in Table 4. Meanwhile, Fig. 3 visually represents the GRA distribution across different parameter levels obtained from the Analysis of Mean in GRA. The main effect plot describes how each design parameter level affects the overall performance, helping to identify the optimal combination of parameters for the copper metallic catalytic converter.

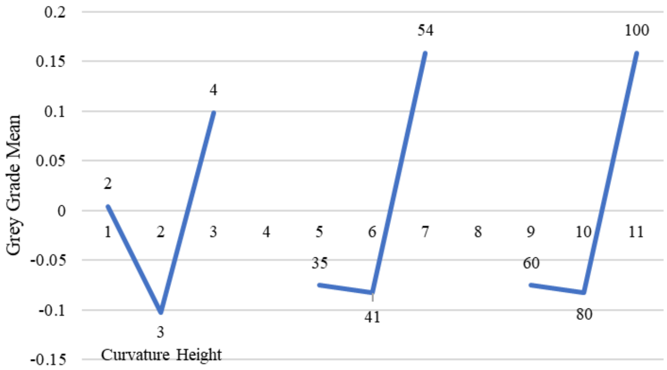

Fig. 3. Main effects chart of Grey Relational Grade

Based on the data in Table 4 and Fig. 2, the catalysts were analyzed according to the average values derived from the calculations of several GRA equations (1-4) and then ranked accordingly. There were eight designs evaluated. Among these, the catalyst with the highest average value was E3, with an average score of 1.000, placing it in the top rank. Catalyst E4 also performed well, with an average of 0.833, securing the second position. These findings align with previous research by Warju et al. [40] and Guo et al. [41], who designed transition metal-based catalytic converters that successfully reduced exhaust gas emissions. The results of this study indicate that the approach used can produce superior catalyst designs based on the ranking of various parameters, similar to the findings for catalysts E3 and E4 in this study.

Next, catalyst E6 achieved an average of 0.713, ranking third in this evaluation. It was followed by catalyst E1, with an average score of 0.692, which placed it in fourth. Catalyst E5 obtained an average of 0.674, ranking fifth. These findings support the research by Ellyanie & Oktabri [42], who analyzed the effects of metal-based converter catalysts on engine performance. Their study also demonstrated that variations in the number and design of catalysts significantly impact engine performance and fuel consumption.

Catalysts STD OEM and E2 had average values of 0.669 and 0.637, placing them in sixth and seventh positions, respectively. Meanwhile, catalyst STD WC had the lowest average score of 0.333, ranking eighth. This result illustrates a comparison of performance between experimental catalysts (such as E2, E3, etc.) and standard catalysts (STD), consistent with the research conducted by Suheni et al. [43], which optimized converter catalyst designs by replacing noble catalysts with copper oxide as a more economical alternative.

This finding is also consistent with research by Ariyanto et al. [44], who investigated the performance of metal-based converter catalysts in reducing exhaust emissions from motorcycle engines. Their study indicated that using metal-based converter catalysts, such as copper-coated chromium, can significantly reduce CO and HC emissions, which aligns with the ranking results of catalysts in this study. This research provides a deeper insight into the enhancement of catalyst performance based on the rankings from GRA calculations.

In line with the findings of Leishman et al. [45], which demonstrates the development of catalyst technology with the best performance for emission control, the alignment between the average values and the rankings of catalysts in this study also reflects the principles discussed in the study on the role of catalyst temperature on emissions by Hata et al. [46], where catalyst performance is related to operational temperature. Thus, this study provides a consistent contribution to the evaluation paradigm for catalyst performance in reducing vehicle emissions, as supported by existing literature.

The E3 catalyst design, with a relatively large curvature height (4 mm), a 54 mm diameter, and a 100 mm length, demonstrated better capability in reducing CO and HC emissions compared to other designs with tighter or smaller curvatures, such as 2 mm or 3 mm curvature heights. Although in theory, a larger surface area of the catalyst can increase the interaction between exhaust gases and the catalyst, the E3 design may have other advantages that contribute to its superior performance.

Several previous studies support this result by pointing to factors beyond the catalyst's surface area that affect catalytic efficiency. For example, research by Irawan et al. [47] showed that the shape and material of the catalyst also play a crucial role in reducing exhaust emissions. Therefore, catalytic efficiency in reducing emissions is not solely dependent on the surface area but also on the composition of materials, shape, and other factors that can influence the interaction between the catalyst and exhaust gases

Table 4. Gray Relational Analysis Results

Catalyst	Average Emissions		x^*_{ij}		GMj		GRj		GRG	RANK
	CO	HC	CO	HC	CO	HC	CO	HC	AVG	
STD WC	5.824	949	0.000	0.000	1.000	1.000	0.333	0.333	0.333	8
STD OEM	4.689	585	0.540	0.888	0.460	0.112	0.521	0.817	0.669	6
E1	4.052	664	0.843	0.696	0.157	0.304	0.762	0.622	0.692	4
E2	4.093	718	0.824	0.563	0.176	0.437	0.740	0.534	0.637	7
E3	3.723	539	1.000	1.000	0.000	0.000	1.000	1.000	1.000	1
E4	4.204	543	0.771	0.990	0.229	0.010	0.686	0.981	0.833	2
E5	5.301	551	0.249	0.973	0.751	0.027	0.400	0.948	0.674	5
E6	4.332	593	0.710	0.870	0.290	0.130	0.633	0.793	0.713	3

Furthermore, research by Ariyanto et al. [48], which optimized catalyst designs using Pareto Optimization, demonstrated the importance of considering various design parameters to achieve better catalytic efficiency. In this case, the diameter and length of the catalyst in the E3 design may have been optimized to achieve a better balance between surface area and other design factors affecting catalytic performance.

Based on the known average values and rankings, catalyst E3 stands out as the design with the best performance. While the E3 catalyst has relatively large curvatures, it excels in terms of diameter and length. This indicates that catalytic efficiency does not solely depend on the surface area of the catalyst. Factors such as shape, material, and other design parameters also play a significant role in improving performance and reducing exhaust emissions. This finding provides additional support for the development of more efficient converter catalysts in reducing vehicle engine exhaust emissions, which is in line with the main objectives of this research.

4 Conclusions

This study demonstrates that the geometric optimization of copper metallic catalytic converters can significantly improve emission performance in automatic motorcycles. Through systematic experimentation and Grey Relational Analysis, the E3 design (featuring a 4 mm curvature height, 54 mm diameter, and 100 mm length) was identified as the optimal configuration, achieving CO emissions of 3.72% Vol and HC emissions of 539 ppm. The research establishes a quantitative relationship between catalyst geometry and emission reduction, validates the superior performance of copper-based catalysts compared to standard designs, and highlights Grey Relational Analysis as an effective tool for optimizing multiple parameters in emission control systems. The results indicate the potential of copper as a cost-effective alternative to precious metals for catalytic converters, especially in emerging markets. By addressing a critical research gap in catalyst design, this study supports the advancement of sustainable vehicle technologies and contributes to global efforts to reduce air pollution and combat climate change.

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