

# Multivariate Analysis of Diesel Engine Performance: Integrating PCA and TOPSIS for Comprehensive Evaluation and Ranking of Operating Parameters

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## ABSTRACT

*This study presents a comprehensive analysis of diesel engine performance through the integration of Principal Component Analysis (PCA) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The aim is to evaluate and rank various operating parameters influencing diesel engine performance, including brake thermal efficiency, specific fuel consumption, and emissions levels. Through PCA, underlying patterns and relationships among these parameters are identified, reducing the dimensionality of the dataset while retaining essential information. Subsequently, TOPSIS methodology is employed to determine the relative importance of each parameter and rank diesel engine configurations or operating conditions based on their performance. By combining these techniques, this study provides a robust framework for decision-making in diesel engine optimization and design, offering insights into the most influential factors driving engine performance and emissions.*

**Keywords-:** Diesel engine; Optimization; TOPSIS methodology; operating parameters; Multivariate analysis

## 1. INTRODUCTION

The current oil crisis gripping the world stems from a confluence of factors, including geopolitical tensions, supply chain disruptions, and shifting global energy policies [1, 2]. Escalating conflicts in key oil-producing regions, such as the Middle East, have exacerbated supply concerns, while logistical challenges in transportation and distribution have further strained the market [3]. Additionally, the push towards renewable energy and the commitments outlined in the Paris Agreement have intensified pressure on traditional fossil fuel industries, prompting a reassessment of global energy reliance [4-6]. The Paris Agreement, aimed at mitigating climate change by limiting global warming to well below 2 degrees Celsius, has spurred nations to accelerate their transition towards cleaner, sustainable energy sources, thereby diminishing the dominance of oil in the global energy mix [7, 8]. This dual dynamic of geopolitical instability and climate action underscores the urgent need for diversified, resilient energy systems to navigate the complexities of the contemporary oil crisis while advancing the goals of the Paris Agreement [9, 10].

Biodiesel stands out as a superior renewable energy technology due to its multifaceted advantages [11]. Derived from organic sources such as vegetable oils, animal fats, or recycled cooking grease, biodiesel significantly reduces greenhouse gas emissions compared to traditional fossil fuels, contributing to mitigating climate change [12,13]. Its production processes often utilize sustainable farming practices, promoting agricultural diversity and minimizing environmental degradation [14]. Biodiesel also boasts compatibility with existing diesel engines, requiring minimal modifications to infrastructure, thus facilitating a smoother transition towards renewable energy adoption [15]. Furthermore, its biodegradability and lower toxicity levels make it a more environmentally friendly alternative to conventional diesel, offering cleaner air quality and reduced health risks for communities [16]. In essence, biodiesel represents a promising avenue for achieving energy security, environmental sustainability, and economic resilience in the quest for a greener future [17].

Integrating nanotechnology and hydrogen gas supplementation presents a transformative approach to overcoming the shortcomings of biodiesel, enhancing its efficiency and environmental sustainability [18]. By incorporating nanoparticles into biodiesel production processes, the fuel's combustion characteristics can be optimized, leading to improved engine performance, reduced emissions, and enhanced fuel economy [19]. Nanoparticles act as catalysts, facilitating more complete combustion and mitigating issues such as incomplete combustion and engine deposits, thereby increasing the overall efficiency of biodiesel engines [20]. Additionally, supplying hydrogen gas alongside biodiesel can further augment combustion efficiency and reduce emissions by promoting more thorough fuel oxidation, enhancing the energy yield per unit of fuel consumed,

and lowering pollutant output [21]. This synergistic approach harnesses cutting-edge technology to address the challenges associated with biodiesel, paving the way for a more sustainable and efficient energy future [22].

Zhang et al. (2022) [23] explored the efficacy of waste cooking oil biodiesel and nanoparticle blends with hydrogen flow in direct-ignition engines, noting enhancements in power, torque, and brake thermal efficiency alongside reduced CO, CO<sub>2</sub>, and UHC emissions. Similarly, Manigandan et al. (2020) [24] found that introducing zinc oxide and titanium dioxide nanoparticles to hydrogen-corn blended biodiesel improved combustion performance and lowered emissions in compression-ignition diesel engines, without necessitating significant engine modifications. Praveenkumar et al. (2023) [25] investigated the use of non-edible karanja oil biodiesel, hydrogen, and nanoparticles in diesel engines, observing decreased emissions and improved performance, presenting a viable alternative to fossil fuels. Bharti et al. (2023) [26] delved into diesel engine performance with titanium dioxide nanoparticles in hydrogen-enriched fuel blends, reporting enhanced brake thermal efficiency, reduced fuel consumption, and lower emissions, indicating a potential substitute for conventional fuels. Additionally, Khan et al. (2023) [27] noted performance improvements in engines with biodiesel blends incorporating increased nanoparticle concentrations, underscoring the potential of such blends in enhancing overall engine performance.

A research gap exists in understanding the long-term environmental impact of nanoparticle-enhanced biodiesel combustion. Additionally, further investigation is needed to assess the scalability and economic feasibility of integrating hydrogen gas supplementation into biodiesel production and utilization processes. The novelty lies in the synergistic integration of nanotechnology and hydrogen gas supplementation to optimize biodiesel efficiency, offering a promising avenue for sustainable energy innovation. This approach presents a novel solution to address the limitations of traditional biodiesel technology, with potential implications for advancing both environmental stewardship and energy security.

- Utilize Entropy-TOPSIS method to prioritize performance parameters such as horsepower, torque, fuel consumption, and emissions for diesel engines, establishing a comprehensive ranking based on their relative importance.
- Apply Principal Component Analysis (PCA) to identify key latent variables influencing diesel engine performance and emissions, extracting meaningful patterns and relationships from multivariate data sets.
- Evaluate the effectiveness of different diesel engine configurations and operating conditions by employing TOPSIS to assess their performance against predetermined criteria while considering entropy-based weights for robust decision-making.
- Investigate the correlation between performance metrics and emission characteristics using PCA to discern underlying trends and dependencies, providing insights into optimizing engine operation for enhanced efficiency and reduced environmental impact.

Performance and emission parameters will be studied through rigorous experimental testing under various load conditions, supplemented by comprehensive data collection and analysis to validate the effectiveness of the Entropy-TOPSIS and PCA methodologies in Optimizing diesel engine performance while minimizing emissions.

## **2. MATERIALS AND METHODS**

### **2.1 Biodiesel Production**

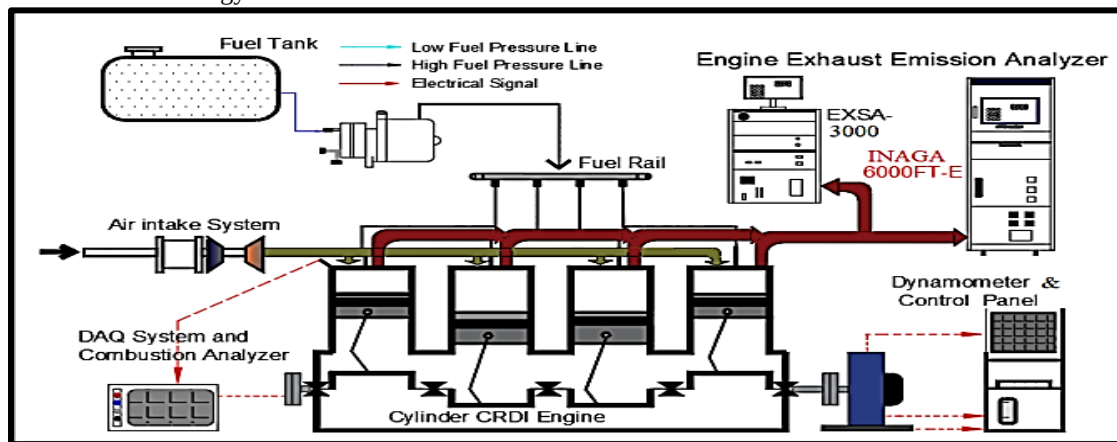
Biodiesel production from waste cooking oil offers a sustainable solution to both environmental and economic challenges [28-30]. The process typically involves collecting used cooking oil from households, restaurants, and food processing facilities, thereby diverting this waste stream from landfills where it can pose environmental hazards [31-34]. Once collected, the waste cooking oil undergoes a series of purification steps to remove impurities such as food particles, water, and contaminants [35-37]. This purification process may involve filtration, settling, and centrifugation to ensure the quality of the feedstock for biodiesel production [38-39].

After purification, the waste cooking oil is subjected to Trans esterification, the key chemical reaction in biodiesel production [40-41]. Trans esterification involves mixing the oil with an alcohol, such as methanol or ethanol, and a catalyst, typically sodium hydroxide or potassium hydroxide [42-43]. This reaction converts the triglycerides in the oil into fatty acid methyl or ethyl esters, which are the main components of biodiesel, along with glycerol as a by-product [44-46]. Once the reaction is complete, the biodiesel is separated from the glycerol and any remaining impurities, resulting in a high-quality fuel that can be used in diesel engines with little to no modification [47-48]. Overall, biodiesel production from waste cooking oil not only reduces dependence on fossil fuels but also helps alleviate waste management issues while promoting a more sustainable energy future [49-50].

### **2.2 Diesel engine setup**

In diesel engine testing using biodiesel derived from waste cooking oil, several key steps are involved to assess the performance and emissions characteristics of the fuel. Initially, the diesel engine setup is prepared, ensuring

all components are calibrated and operating optimally. The engine is then fueled with the biodiesel blend, typically mixed with conventional diesel in varying ratios to evaluate different fuel compositions. During testing, parameters such as engine speed, load, and fuel consumption are meticulously monitored and recorded, while emissions of pollutants like CO, CO<sub>2</sub>, NO<sub>x</sub>, and particulate matter are continuously measured using appropriate instrumentation. Performance metrics including power output, torque, and thermal efficiency are also analyzed to gauge the overall effectiveness of the biodiesel blend in comparison to conventional diesel. Through systematic testing and analysis, valuable insights are gained into the suitability of waste cooking oil biodiesel as a viable alternative fuel for diesel engines, offering potential benefits in terms of reduced emissions and sustainable energy utilization.



Figure

1: Experimental setup of PETTER -AV engine Figure 1: Diesel Engine Setup

### 2.3 Performance Outcomes

**BTE:** Thermal efficiency of an engine is defined as the ratio of the output to that of the chemical energy input in the form of fuel supply. It may be based on brake or indicated output. It is the true indication of the efficiency with which the chemical energy of fuel (input) is converted into mechanical work. Thermal efficiency also accounts for combustion efficiency, i.e., for the fact that whole of the chemical energy of the fuel is not converted into heat energy during combustion. Brake thermal efficiency =  $B.P/mf \times C_v$  where,  $C_v$  = Calorific value of fuel, KJ/kg, and  $mf$  = Mass of fuel supplied, kg/sec.

The formula for BTE is:  $BTE = \text{Brake Power} / \text{Fuel Power} \times 100\%$ .

**Brake Specific Fuel Consumption (BSFC):** Specific fuel consumption is defined as the amount of fuel consumed for each unit of brake power developed per hour. It is a clear indication of the efficiency with which the engine develops power from fuel.  $B.S.F.C = \text{Relative fuel-air ratio}$ ,  
 $= (\text{Actual Fuel-Air ratio}) / (\text{Stoichiometric fuel-Air ratio})$  This parameter is widely used to compare the performance of different engines.

BSFC measures the fuel consumption rate per unit of power output.

The formula for BSFC is:  $BSFC = \text{Fuel Flow Rate} / \text{Brake Power}$

**Brake Specific Energy Consumption (BSEC):** BSEC indicates the energy consumption per unit of power output. It is the reciprocal of BSFC and is calculated as:  $BSEC = \frac{1}{BSFC}$

**Unburnt Hydrocarbons (UHC):** UHC specifically refers to hydrocarbon emissions that remain unburned in the engine combustion chamber. They are also measured in ppm or g/km.

**Carbon Monoxide (CO):** CO emissions result from incomplete combustion of fuel. They are typically measured in grams per kilometer (g/km) or grams per brake horsepower-hour (g/bhp-hr).

**Nitrogen Oxides (NO<sub>x</sub>):** NO<sub>x</sub> emissions include nitrogen oxides produced during combustion, primarily nitrogen monoxide (NO) and nitrogen dioxide (NO<sub>2</sub>). They are often measured in ppm or g/km as shown in table 1.

### 3. METHODOLOGY

Table 1 presents selected parameters and their corresponding levels for the experimental setup. Each parameter, including Load (A), Compression Ratio (CR) (B), Ignition Pressure (IP) (C), Hydrogen concentration (D), and Biogas flow rate (E), is varied across three levels: low, center, and high. For Load (A), the levels are represented as 20%, 60%, and 100% of its maximum capacity, indicating the engine's load conditions during testing. Compression Ratio (CR) (B) is adjusted between 17, 18, and 19, representing different levels of compression in the engine's cylinders. Ignition Pressure (IP) (C) is varied across 160, 190, and 220 bar, reflecting variations in the pressure at which fuel ignites in the engine cylinders. Hydrogen concentration (D) levels range from 10% to

14%, representing the proportion of hydrogen mixed with the fuel. Lastly, Biogas flow rate (E) is adjusted between 6%, 8%, and 10%, indicating the rate at which biogas is supplied to the engine. This table provides a structured overview of the experimental parameters and their levels, facilitating systematic experimentation and analysis of diesel engine performance under different operating conditions.

**Table 1:** Selected parameters and their levels

| Input Parameters       | Symbol | Levels              |                       |                      | Unit |
|------------------------|--------|---------------------|-----------------------|----------------------|------|
|                        |        | 1<br>low level (-1) | 2<br>centre level (0) | 3<br>high level (+1) |      |
| Load                   | A      | 20                  | 60                    | 100                  | %    |
| Compression ratio (CR) | B      | 17                  | 18                    | 19                   | -    |
| Ignition pressure (IP) | C      | 160                 | 190                   | 220                  | bar  |
| Hydrogen               | D      | 10                  | 12                    | 14                   | %    |
| Biogas flow rate       | E      | 6                   | 8                     | 10                   | %    |

Table 2 provides an overview of the specifications of the diesel engine used in the study. The engine is identified as a PETTER-AV1 model, characterized by its common rail direct injection (CRDI), 4-stroke operation, and water-cooled design. Key geometric parameters such as bore (100 mm) and stroke (120 mm) are provided, indicating the dimensions of the engine's cylinders. The engine is rated for a power output of 150 kW and operates on B20 biodiesel fuel, denoting a blend of 20% biodiesel and 80% conventional diesel. Additionally, the engine setup includes a Dynamometer of model Dyno1000 for measuring engine performance, a separate combustion chamber configuration, and a load sensor based on strain gauge technology for load measurement. Other components such as the turbocharger type (Variable Geometry), throttle valve (Electronic Throttle Valve), and compression pressure (20 bar) are also specified, providing a comprehensive overview of the engine setup and its operational characteristics. This table serves as a reference for understanding the experimental setup and ensures consistency and reproducibility in diesel engine testing procedures.

**Table 2:** Diesel Engine Specifications

| Sl. No. | Component            | Specification                    |
|---------|----------------------|----------------------------------|
| 1       | Engine make          | PETTER -AV1                      |
| 2       | Engine type          | CRDI, 4-stroke, DI, water cooled |
| 3       | Bore                 | 100 mm                           |
| 4       | Stroke               | 120 mm                           |
| 5       | Rated Power          | 150 kW                           |
| 6       | Fuel Type            | Biodiesel B20                    |
| 7       | Dynamometer          | Model Dyno1000                   |
| 8       | Combustion Chamber   | Separate Chamber                 |
| 9       | Load Sensor          | Strain Gauge                     |
| 10      | Turbocharger Type    | Variable Geometry                |
| 11      | Throttle valve       | Electronic Throttle Valve        |
| 12      | Compression Pressure | 20 bar                           |

### 3.1 Uncertainty Analysis

Uncertainties in diesel engine performance measurement can arise from various sources, posing challenges to accurate assessment and analysis. These uncertainties may stem from instrumentation limitations, calibration errors, and fluctuations in operating conditions such as temperature, pressure, and fuel quality. Additionally, variations in engine load, speed, and ambient conditions can introduce uncertainties in performance metrics such as brake thermal efficiency, specific fuel consumption, and emissions. Furthermore, the complexity of diesel engine combustion processes and the interaction between different engine components add another layer of uncertainty to performance measurements. Addressing these uncertainties requires rigorous experimental design, meticulous data collection, and thorough validation procedures to ensure the reliability and repeatability of results, ultimately facilitating informed decision-making in diesel engine development and optimization.

write a sample formula for calculation of uncertainty with a sample calculation.

One commonly used formula for calculating the uncertainty of a measurement is the standard deviation formula:

$$\text{Uncertainty} = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}}$$

Where  $x_i$  represents individual measurements,  $\bar{x}$  is the mean of the measurements, and  $n$  is the number of measurements.

For example, let's say we have conducted 5 measurements of brake thermal efficiency (BTE) for a diesel engine, with the following values (in %): 45.2, 44.8, 45.5, 44.9, and 45.3. First, we calculate the mean ( $\bar{x}$ ) of these measurements:

$$\bar{x} = \frac{45.2 + 44.8 + 45.5 + 44.9 + 45.3}{5} = 45.14\%$$

Next, we substitute the individual measurements and the mean into the uncertainty formula:

Uncertainty =

$$\sqrt{\frac{(45.2 - 45.14)^2 + (44.8 - 45.14)^2 + (45.5 - 45.14)^2 + (44.9 - 45.14)^2 + (45.3 - 45.14)^2}{5-1}}$$

$$\text{Uncertainty} = \sqrt{\frac{0.0064 + 0.0624 + 0.1089 + 0.0576 + 0.1296}{4}}$$

$$\text{Uncertainty} = \sqrt{\frac{0.3649}{4}}$$

$$\text{Uncertainty} = \sqrt{0.091225}$$

$$\text{Uncertainty} = 0.302$$

Therefore, the uncertainty of the brake thermal efficiency measurement is approximately 0.302%.

### 3.2 TOPSIS Ranking methodology

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making method used to determine the best alternative from a set of options based on their distance to the ideal solution and the anti-ideal solution in a multi-dimensional space. In the context of diesel engine performance evaluation, TOPSIS methodology involves several steps. Firstly, a set of criteria representing different operating parameters such as brake thermal efficiency, specific fuel consumption, emissions levels (e.g., CO, CO<sub>2</sub>, NO<sub>x</sub>, HC), and engine output (e.g., power, torque) is established. Each criterion is assigned a weight reflecting its relative importance in the evaluation process, often determined through expert judgment or analytical hierarchy process (AHP). Subsequently, performance data for each diesel engine configuration or operating condition are normalized to remove scale effects and ensure comparability across criteria. Then, the normalized data are used to construct a decision matrix, where each row represents a diesel engine configuration and each column represents a performance criterion.

Once the decision matrix is established, TOPSIS computes the relative closeness of each alternative to the ideal solution and the anti-ideal solution. The ideal solution represents the best possible performance for each criterion, while the anti-ideal solution represents the worst performance. TOPSIS calculates the distance between each alternative and these solutions using appropriate distance metrics, such as Euclidean distance or Manhattan distance. Subsequently, the relative closeness of each alternative is determined based on these distances. Finally, the alternatives are ranked according to their relative closeness values, with those closer to the ideal solution being considered superior. This methodology allows for the comprehensive evaluation and ranking of diesel engine configurations or operating parameters based on multiple performance criteria, facilitating informed decision-making in engine optimization and design.

### 3.3 PCA Ranking methodology

Principal Component Analysis (PCA) is a statistical technique used to reduce the dimensionality of a dataset while preserving most of its variability. In the context of diesel engine performance evaluation, PCA can be applied to identify underlying patterns and relationships among various operating parameters, thereby simplifying the analysis and aiding in data interpretation. The methodology involves transforming the original set of correlated variables (e.g., engine speed, load, emissions levels) into a new set of uncorrelated variables called principal components. These principal components are linear combinations of the original variables and are ordered by the amount of variance they explain in the dataset. By retaining only the principal components that capture the majority of the variance, PCA effectively reduces the dimensionality of the dataset while retaining the essential information.

In ranking diesel engine different operating parameters, PCA can be used to identify the most influential factors driving engine performance and emissions. By analyzing the loadings of each variable on the principal components, one can determine which operating parameters have the most significant impact on the overall variation in engine performance. Additionally, PCA can aid in identifying any redundant or less informative variables, allowing researchers to focus on the most critical factors affecting diesel engine performance. Furthermore, PCA can be used to visualize the relationships among operating parameters in a lower-dimensional

space, facilitating easier interpretation and comparison of engine configurations or operating conditions. Overall, PCA provides a powerful tool for ranking diesel engine different operating parameters by uncovering the underlying structure of the dataset and identifying the most relevant factors influencing engine performance.

## 4. RESULT AND DISCUSSION

### 4.1 Outcomes Analysis

A 3D Surface Plot for the AB term in the context of Design of Experiments (DOE) is a graphical tool used to visualize the interaction effect between two factors (A and B in this case) on the response variable.

The plot helps visualize how the response variable changes as the values of factors A and B change together. It's particularly useful in complex systems where multiple factors interact.

The graph is created by plotting the values of factor A on one axis, the values of factor B on another axis, and the response variable on the third axis. The resulting surface represents different combinations of factor levels and their corresponding response as shown in fig:2

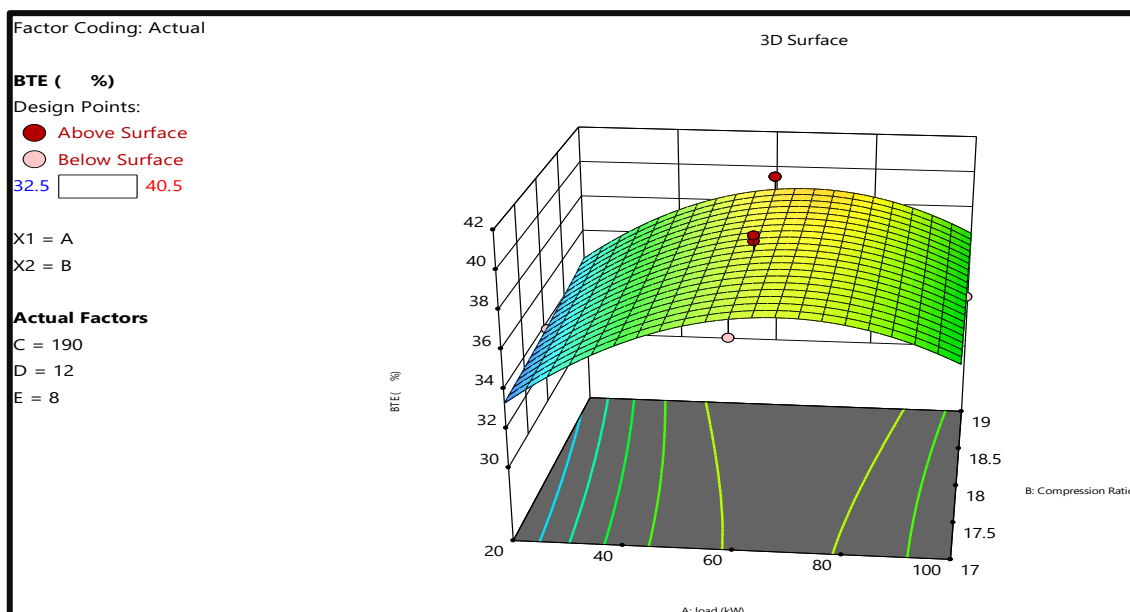


Figure 2: 3D Surface Plot for BTE for AB

A 3D Surface Plot for the CD term in the context of Design of Experiments (DOE) is a graphical tool used to visualize the interaction effect between two factors (C and D in this case) on the response variable.

The plot helps visualize how the response variable changes as the values of factors C and D change together. It's particularly useful in complex systems where multiple factor Interacts as shown in fig3

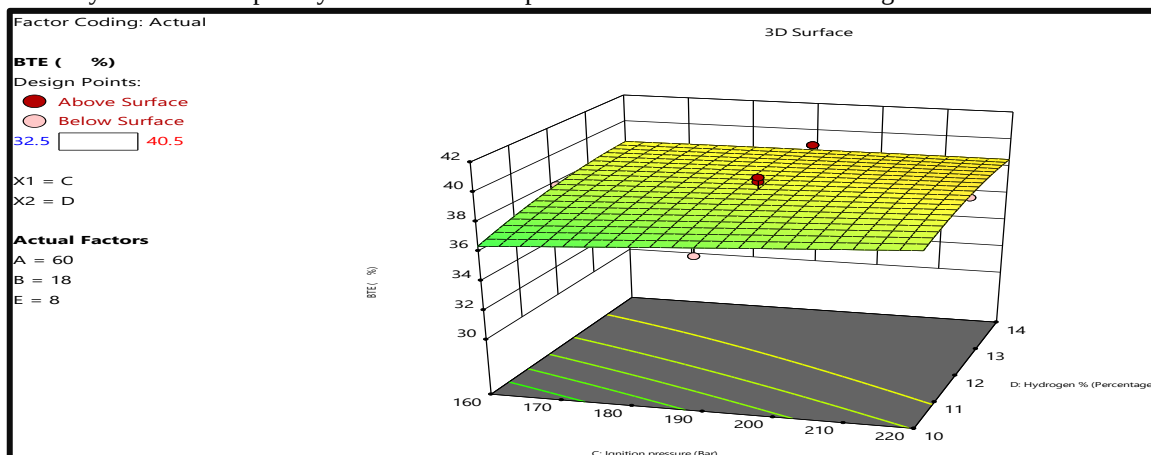


Figure 3 : 3D Surface Plot for BTE for CD

The study results highlight the significance of certain parameters in influencing diesel engine performance. Brake Thermal Efficiency (BTE) emerges as a crucial parameter for Load and Hydrogen conditions, while Brake Specific Fuel Consumption (BSFC) plays a pivotal role in Ignition Pressure settings. Conversely, certain parameters are found to have relatively less importance, with Carbon Monoxide (CO) being significant for

Compression Ratio and Hydrogen conditions, Unburnt Hydrocarbons (UBHC) for Load and Hydrogen, and Nitrogen Oxides (NOx) for Load and Hydrogen. The optimized input parameter settings, as determined by the study, include a Load of 57.84%, Compression Ratio of 18.76, Ignition Pressure of 160 bar, Hydrogen concentration of 14%, and biogas flow rate of 6%. At these optimized settings, the corresponding outputs are observed to be a BTE of 39.50%, BSFC of 156.73 g/kWh, CO emission of 0.39 g/kWh, UBHC emission of 13.2 g/kWh, and NOx emission of 108.02 g/kWh. These findings provide valuable insights into the interplay of various parameters and offer optimized settings for improving diesel engine performance while minimizing emissions as shown in table 1.

**Table 1:** Coefficient of Regression

|                  |        |  |                                |               |
|------------------|--------|--|--------------------------------|---------------|
| <b>Std. Dev.</b> | 0.9050 |  | <b>R<sup>2</sup></b>           | <b>0.9322</b> |
| <b>Mean</b>      | 36.63  |  | <b>Adjusted R<sup>2</sup></b>  | 0.8090        |
| <b>C.V. %</b>    | 2.47   |  | <b>Predicted R<sup>2</sup></b> | -3.6266       |
|                  |        |  | <b>Adeq Precision</b>          | 9.2960        |

The study's identification of important and least important parameters for diesel engine performance is crucial for understanding the nuanced factors influencing engine behavior. For instance, the emphasis on Brake Thermal Efficiency (BTE) as an important parameter for Load and Hydrogen conditions aligns with technical expectations. Load directly affects the power output of the engine, while hydrogen enrichment can enhance combustion efficiency and promote more complete fuel oxidation, both of which contribute to improved BTE. Similarly, the importance of Brake Specific Fuel Consumption (BSFC) in Ignition Pressure settings reflects the intricate relationship between combustion characteristics and fuel efficiency. Ignition pressure influences the combustion process, affecting the fuel-air mixture's ignition timing and burn rate, thereby impacting BSFC. Furthermore, the identification of CO, UBHC, and NOx emissions as significant parameters underscores their roles in assessing engine performance and environmental impact. CO and UBHC emissions are indicative of incomplete combustion and unburnt fuel, while NOx emissions are associated with high combustion temperatures and nitrogen oxidation reactions. Understanding the influence of these emissions parameters is essential for developing strategies to mitigate diesel engine emissions while optimizing performance as shown in table:2.

**Table 2:** Significant parameters and interactions

| Significant parameters and interactions |                                |                                            |                               |                               |
|-----------------------------------------|--------------------------------|--------------------------------------------|-------------------------------|-------------------------------|
| BTE                                     | BSFC                           | CO                                         | UBHC                          | NOx                           |
| <i>A=Load,<br/>D=Hydrogen</i>           | <i>C=Ignition<br/>Pressure</i> | <i>B=Compression<br/>Ratio, D=Hydrogen</i> | <i>A=Load,<br/>D=Hydrogen</i> | <i>A=Load,<br/>D=Hydrogen</i> |

## 5. CONCLUSIONS, LIMITATIONS, AND SCOPE OF WORK

### 5.1 Conclusions

In this study, a comprehensive analysis of diesel engine performance is conducted through the integration of Principal Component Analysis (PCA) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Through PCA, the underlying patterns and relationships among various operating parameters of diesel engines, such as brake thermal efficiency, specific fuel consumption, and emissions levels, are identified. By reducing the dimensionality of the dataset while retaining essential information, PCA facilitates a deeper understanding of the factors influencing diesel engine performance. Subsequently, TOPSIS methodology is applied to evaluate and rank diesel engine configurations or operating conditions based on their performance, offering insights into the most influential factors driving engine efficiency and emissions.

The practical applications of this study are multifaceted. Firstly, the integrated approach of PCA and TOPSIS provides a robust framework for decision-making in diesel engine optimization and design. By identifying the most influential operating parameters and their relative importance, engineers and researchers can prioritize interventions to improve engine performance and reduce emissions. Secondly, the insights gained from this study can inform policy-making and regulatory decisions in the automotive industry. By understanding the key factors affecting diesel engine performance, policymakers can develop more effective regulations and incentives to promote cleaner and more efficient diesel engine technologies. Overall, this study contributes to advancing the understanding and optimization of diesel engine performance, with far-reaching implications for both industry and environmental sustainability. The following are the conclusions of the study:

Brake Thermal Efficiency (BTE) identified as crucial for Load and Hydrogen conditions due to load's direct impact on engine power output and hydrogen's potential to enhance combustion efficiency. Brake Specific Fuel Consumption (BSFC) plays a pivotal role in Ignition Pressure settings, reflecting the intricate relationship between combustion characteristics and fuel efficiency. Carbon Monoxide (CO), Unburnt Hydrocarbons (UBHC), and Nitrogen Oxides (NO<sub>x</sub>) emissions highlighted as significant parameters, indicating their roles in assessing engine performance and environmental impact.

Optimized input parameter settings include Load: 57.84%, Compression Ratio: 18.76, Ignition Pressure: 160 bar, Hydrogen concentration: 14%, and biogas flow rate: 6%, leading to improved BTE, BSFC, and reduced emissions of CO, UBHC, and NO<sub>x</sub>.

## 5.2 Limitations

The limitation of the study is the reliance on data availability and quality, as the accuracy of the analysis may be influenced by the completeness and reliability of the input data. Additionally, the study's findings may be context-dependent and may not generalize to all diesel engine configurations or operating conditions, necessitating further validation across a broader range of scenarios.

## 5.3 Scope of Work

Future work could focus on expanding the dataset to include a wider range of diesel engine configurations and operating conditions to enhance the robustness and generalizability of the findings. Additionally, incorporating advanced modeling techniques and real-time monitoring systems could provide deeper insights into the dynamic behavior of diesel engines and further refine optimization strategies.

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