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Optimal Fuel Selection Using a Hybrid VIKOR-TOPSIS Approach: A Comprehensive Analysis of Environmental Regulations and Road Transport Pollutant Emissions

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ABSTRACT

The increasing global demand for fuel, driven by population growth and transportation expansion, has resulted in significant environmental and health challenges due to emissions from fossil fuels, particularly diesel. This study presents a hybrid Multi-Criteria Decision-Making (MCDM) approach that combines ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Criteria Importance Through Inter-Criteria Correlation (CRITIC) methods to evaluate and rank six fuel alternatives based on their performance and environmental impact. Key performance indicators, including brake thermal efficiency, exhaust gas temperature, mass flow rate, and air-fuel ratio, were analyzed to assess their effect on engine efficiency and pollutant emissions. The results showed that diesel with gasoline fumigation (D+GF) ranked first in most scenarios, including RC1 and RC5, while B20 (80% diesel, 20% biodiesel) ranked second in all cases except RC6, where it ranked third. B20 was found to be more suitable for high-pollution areas due to its lower emissions. The study demonstrated that D+GF improved engine efficiency by 10% compared to pure diesel and reduced emissions by up to 15% under certain conditions. This research highlights the importance of adopting cleaner fuels and recommends integrating advanced MCDM techniques, such as fuzzy MCDM and machine learning-aided MCDM, for future assessments.

1. INTRODUCTION

The rapid expansion of cities and increasing transportation demands have significantly raised fossil fuel consumption, particularly diesel, contributing to severe environmental and health challenges. Diesel engines emit harmful pollutants, including particulate matter (PM2.5), nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC), all of which significantly degrade air quality and contribute to the development of respiratory and cardiovascular diseases [1-5]. According to the World Health Organization (WHO), these pollutants are responsible for over 4.2 million premature deaths annually, primarily due to diseases linked to air pollution [6, 7].

As a result, there has been growing interest in alternative fuels such as biodiesel, which offer a cleaner and more sustainable option for reducing emissions. Biodiesel, especially in blends such as B20, has been demonstrated to significantly lower emissions of particulate matter (PM2.5), hydrocarbons, and carbon monoxide, positioning it as a viable alternative to conventional diesel in efforts to reduce environmental pollution [8-10]. Introducing gasoline into diesel engines through fumigation has been explored as a way to improve the combustion process, increase fuel efficiency, and reduce emissions, offering a potential solution for cleaner fuel usage in diesel-powered vehicles [9-11].

Several factors, including the air/fuel ratio, exhaust gas temperature, and the mass flow rates of the fuels involved, influence the combustion process in diesel engines. This study employs a hybrid Multi-Criteria Decision-Making (MCDM) approach, integrating VIKOR, TOPSIS, and CRITIC methods, to evaluate and rank six fuel alternatives based on their performance and environmental impact. The study found that diesel with gasoline fumigation (D+GF) consistently ranked first in terms of improving engine efficiency and reducing emissions, particularly in scenarios such as RC1 and RC5. Meanwhile, B20 (a blend of 80% diesel and 20% biodiesel) was ranked second, demonstrating its potential for high-pollution areas due to its lower emissions compared to pure diesel [12-15].

This research highlights the significant role of alternative fuels and innovative combustion techniques in reducing harmful emissions and improving engine efficiency. By applying advanced MCDM methods, the study provides a comprehensive decision-making framework that aids in selecting the most effective fuel combinations to meet environmental regulations and enhance sustainability in the transportation sector.

2. METHODOLOGY

This study employs a hybrid MCDM approach that integrates three well-established techniques: Criteria Importance Through Inter-Criteria Correlation (CRITIC), ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [16-18]. As illustrated in Figure 1, the methodology follows a structured sequence of steps to evaluate and rank six fuel alternatives based on performance and environmental indicators.

The hybrid MCDM approach used in this study is based on a unique integration of CRITIC, VIKOR, and TOPSIS. Initially, CRITIC is applied to assign objective weights to the criteria based on their variability and inter-criteria correlation. These weights are then used in the VIKOR and TOPSIS methods to rank the alternatives. The novelty of this approach lies in the sequencing of these methods, ensuring that the most important criteria, as identified by CRITIC, are given the highest priority in the ranking process. Additionally, a new aggregation method is employed that combines both utility and regret measures from VIKOR and TOPSIS, offering a more comprehensive decision-making framework than traditional methods.

2.1 Data collection

The experimental data are based on Hoseinpour et al. [13], who tested six fuel configurations on a naturally aspirated, four-cylinder, water-cooled, direct-injection (DI) diesel engine. The engine was operated under various loads, 25%, 50%, and 75% of full brake mean adequate pressure (BMEP) and at two speeds (1,300 rpm and 2,000 rpm). The fuel cases tested include:

Code	Fuel Description
A	Diesel fuel
B	Diesel with gasoline fumigation (D+GF)
C	80% diesel + 20% biodiesel (B20)
D	B20 with gasoline fumigation (B20+GF)

Performance criteria included:

- Brake Thermal Efficiency (BTE)
- Exhaust Gas Temperature (EGT)
- Base Fuel Flow Rate (Gb)
- Gasoline Flow Rate (Gf)
- Air/Fuel Ratio (AFR)

2.2 CRITIC method for weight assignment

The CRITIC method assigns objective weights to each criterion by combining variability (standard deviation) and conflict (correlation between criteria) [19-22].

Step 1: Normalize the decision matrix using Eq. (1):

$$a_{ij}^{+} = \frac{a_{ij} - a_j^{\min}}{a_j^{\max} - a_j^{\min}} \tag{1}$$

Step 2: Compute the amount of information (C_j) using Eq. (2):

$$C_j = \sigma_j \cdot \sum_{k=1}^{n} (1 - r_{jk}) \tag{2}$$

Step 3: Determine objective weights (w_j) using Eq. (3):

$$w_j = \frac{C_j}{\sum_{j=1}^{m} C_j} \tag{3}$$

This ensures that criteria with high variability and low correlation are assigned greater weights.

2.3 VIKOR method for ranking

The VIKOR method ranks alternatives based on their proximity to the ideal solution, considering both utility and regret measures.

Step 1: Normalize the decision matrix (same as CRITIC).

Step 2: Identify best and worst values using Eqs. (4) and (5):

$$f_j^* = Max_i f_{ij}, f_j^- = Min_i f_{ij} \quad j=1, 2\ldots, n \tag{4}$$

$$f_j^* = Min_i f_{ij}, f_j^- = Max_i f_{ij} \quad j=1, 2\ldots, n \tag{5}$$

Eqs. (4) and (5) were revised to properly define benefit and cost criteria. Eq. (4) now defines the benefit criteria with the **max** operator, and Eq. (5) defines the cost criteria with the **min** operator. This ensures consistency in how benefit and cost criteria are treated in the ranking process.

Step 3: Calculate S and R values using Eqs. (6) and (7):

$$S_i = \sum_j w_j \cdot \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \tag{6}$$

$$R_i = \max_j \left[w_j \cdot \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right] \tag{7}$$

Step 4: Compute VIKOR index (Q_i) using Eq. (8):

$$Q_i = v \cdot \frac{S_i - S^*}{S^- - S^*} + (1 - v) \cdot \frac{R_i - R^*}{R^- - R^*} \tag{8}$$

where,

$$S^* = Min_i\{S_i\}; S^- = Max_i\{S_i\};$$
$$R^* = Min_i\{R_i\};\ R^- = Max_i\{R_i\}.$$

v=0.5 is for balanced decision-making.

Step 5: Rank alternatives in ascending order by Q_i values.

2.4 TOPSIS method for final evaluation

The TOPSIS method identifies the alternative closest to the positive ideal solution and farthest from the negative ideal.

Step 1: Create a normalized matrix using Eq. (9):

$$f_{ij}(\mathrm{x}) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{9}$$

Step 2: Determine the weighted normalized matrix using Eq. (10):

$$V_{ij} = r_{ij} \times W_j \tag{10}$$

where, W_j are the weights of the criteria and are given by the entropy method.

Step 3: Obtain the maximum z^+ and minimum scores z^- for each column using Eqs. (11)-(14):

$$Z^+ = \underbrace{max}_{n}\{V_{ij}\} = \{Z_1^+, Z_2^+, Z_3^+\} \tag{11}$$

$$Z^- = \underbrace{min}_{n}\{V_{ij}\} = \{Z_1^-, Z_2^-, Z_3^-\} \tag{12}$$

$$\alpha_n^+ = \sqrt{(V_{i1} - Z_1^+)^2 + (V_{i2} - Z_2^+)^2 + (V_{i3} - Z_3^+)^2} \tag{13}$$

$$\alpha_n^- = \sqrt{(V_{i1} - Z_1^-)^2 + (V_{i2} - Z_2^-)^2 + (V_{i3} - Z_3^-)^2} \quad i=1, 2\ldots, n \tag{14}$$

Step 4: The final ranking index should be created.

The FRIn [23-28] is a credible ranking index that defines the basis for the ultimate ranking. For MCDM techniques, we consider the separation distance, which can be defined as the distance between the positive ideal solution and the negative ideal solution for the ranking index in the proposed model.

Eq. (15) (FRIn) offers a unique aggregation formula compared to the traditional TOPSIS relative closeness formula, $C_i = a_n^- / (a_n^- + a_n^+)$. The main advantage of using FRIn is its ability to combine both utility and regret measures from VIKOR and TOPSIS, providing a more comprehensive decision-making framework. Unlike the traditional TOPSIS formula, which primarily focuses on the relative closeness of each alternative to the ideal solution, the FRIn formula allows for a more nuanced ranking, incorporating both the utility of preferred criteria and the regret associated with non-preferred criteria. This enhances the precision and robustness of the decision-making process, making it more applicable to complex problems with multiple conflicting criteria.

$$FRI_n = \alpha_n^- n = 1m\alpha n - \left(\frac{\alpha_n^+}{\sum_{n=1}^{m} \alpha_n^+}\right) \quad -1 \le FRI_n \le 1 \tag{15}$$

Alternatives are ranked in descending order of C_i.

This methodology enables systematic evaluation and comparison of fuel alternatives by integrating performance data, statistical weighting, compromise solutions, and proximity to ideal values.

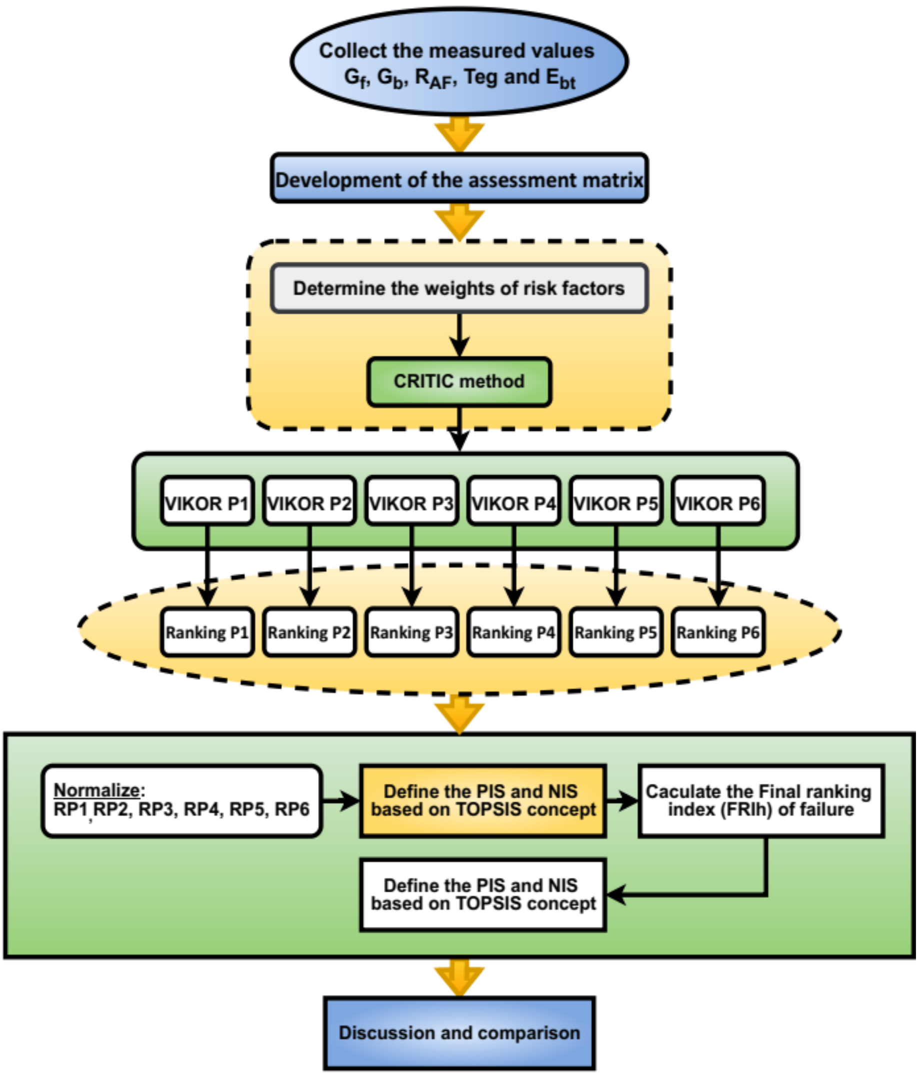

Figure 1. Hybrid MCDM methodology overview

3. CASE STUDY

In this study, a hybrid MCDM method is employed to evaluate the performance of a 4-cylinder, indirect-injection automotive diesel engine (Figure 2). The engine operates with various fuel types, including:

- Gasoline-fumed diesel (D+GF)
- B20 (a blend of 80% diesel and 20% biodiesel)
- Pure biodiesel
- Conventional diesel

The primary goal of this case study is to evaluate the performance of these fuels across multiple criteria, including fuel efficiency, engine power output, emissions, and environmental impact. By employing the hybrid MCDM approach, which combines various decision-making techniques such as CRITIC, VIKOR, and TOPSIS, the study aims to provide a robust and reliable evaluation.

Key Performance Indicators (KPIs):

- **Energy Conversion:** A Measure of how effectively each fuel type converts energy into practical work.
- **Engine Power Output:** The power generated by the engine using different fuels.
- **Emissions:** Measurement of pollutants emitted by the engine, such as NOx, CO, HC, and PM2.5.
- **Environmental Impact:** An analysis of the environmental footprint of each fuel, considering factors such as greenhouse gas emissions and sustainability [29].

While the study focuses on tailpipe emissions, it is also important to consider the well-to-wheel impacts of the fuels analyzed. Well-to-wheel analysis includes the energy required to produce, process, and transport fuels, as well as the emissions associated with their production. For biodiesel, this includes the energy required for cultivating feedstocks, refining, and transportation, which can contribute significantly to its overall environmental footprint. Studies have shown that while biodiesel may reduce tailpipe emissions, its production energy and land use can offset some of these benefits, particularly when compared to conventional diesel. A comprehensive environmental impact analysis, therefore, should consider both the direct emissions from the engine and the indirect emissions from fuel production.

This integrated approach provides a comprehensive evaluation that considers not only the operational performance of the engine but also the environmental and economic impacts of each fuel type. By combining these diverse factors, the study presents a well-structured framework for ranking and selecting the most suitable fuel alternative for automotive applications, considering both technical and ecological requirements.

Figure 2 illustrates the experimental setup for evaluating fuel performance in a 4-cylinder, indirect-injection automotive diesel engine. The engine has a displacement of 2.0 liters and operates with an injection pressure of 1500 bar. These specifications are crucial for understanding the engine's combustion process and how different fuel types perform under varying operational conditions. The setup also includes various sensors and components, such as the airflow sensor, exhaust temperature sensor, and fuel injectors, to monitor and optimize engine performance and emissions.

The experimental setup for evaluating fuel performance in the 4-cylinder indirect injection automotive diesel engine includes several key components. These include the engine (1), which is the core unit for combustion, and the crankshaft (2), which converts the pistons' linear motion into rotational motion. The camshaft (3) controls the intake and exhaust valves, while the camshaft speed sensor (4) and crankshaft speed sensor (5) monitor the rotation speeds. The electronic control unit (ECU) (6) manages engine parameters, including fuel injection and air-fuel ratios. Fuel is supplied via the gasoline pump and tank (7) and distributed through the fuel rail (8) to the port fuel injectors (9). The airflow sensor (10) monitors the incoming air, which is then directed through the intake manifold (11). The direct injector (12) injects diesel fuel into the combustion chamber, supported by the diesel pump (13) and diesel fuel tank (14). The dynamometer (15) measures power output, while the gas analyzer (16) and opacimeter (17) assess emissions. Finally, the exhaust temperature sensor (18) ensures the engine operates within optimal thermal conditions. In the following sections, we will discuss the methodology used to rank and select the optimal fuel based on these criteria, as well as the results derived from applying the hybrid MCDM method.

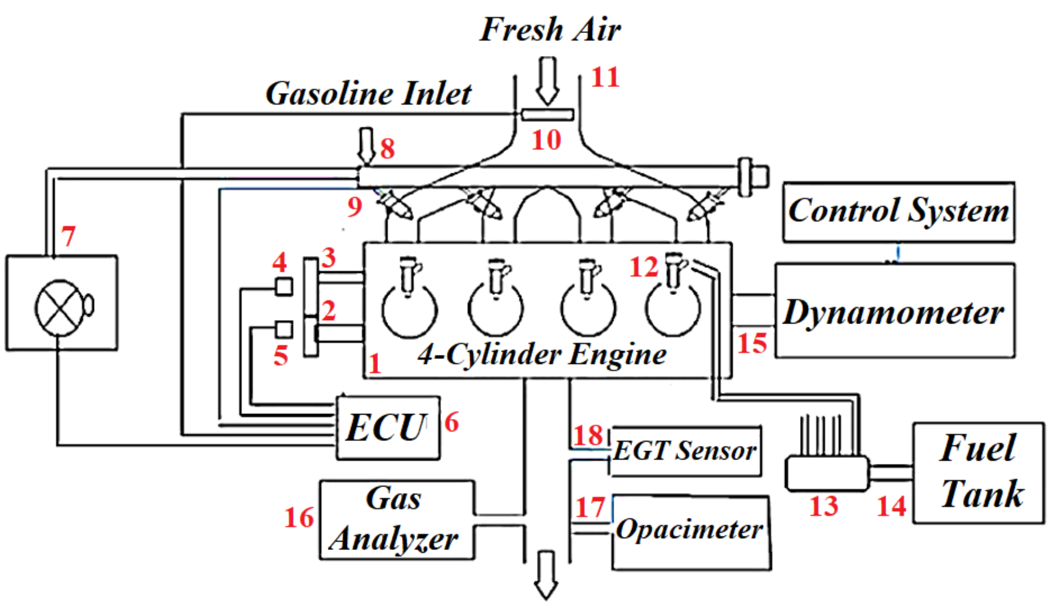

Figure 2. Cylinder indirect injection automotive diesel engine setup

4. RESULTS AND DISCUSSION

In this study, a comprehensive MCDM approach, incorporating the CRITIC, VIKOR, and TOPSIS methods, was employed to evaluate the performance of six alternative fuel types in a 4-cylinder automotive diesel engine. The analysis was based on five key performance indicators: gasoline mass flow rate (Gf), base fuel flow rate (Gb), air/fuel ratio (RAF), exhaust gas temperature (Teg), and brake thermal efficiency (Ebt). The experimental data used in this study were sourced from references [13, 25-31].

4.1 Decision matrices for different engine conditions

We constructed decision matrices to evaluate the performance of each fuel type under varying engine operating conditions. These matrices represent key criteria across six test cases (RC1 to RC6) as shown in Table 1, providing a comprehensive view of fuel performance. The matrices were used to calculate the weights for each criterion using the CRITIC method, ensuring an unbiased evaluation based on the relative importance of each criterion.

4.2 CRITIC method for weight estimation

The CRITIC method was used to assign weights to each criterion based on its variability and correlation with other criteria. The results, shown in Table 2, indicate that the gasoline mass flow rate (Gf) and exhaust gas temperature (Teg) are the most influential parameters, given their high variability across the different fuel types.

Table 1. Decision matrix for case 1 (N = 1300 rpm, Load = 25%, BMEP = 2.1 bar)

Fuel Type	Gf (kg/h)	Gb (kg/h)	RAF	Teg (K)	Ebt
Fuel 1	Diesel	0	2.41	61.89	227
Fuel 2	D+FG1	0.35	1.91	58.64	220
Fuel 3	D+FG2	0.7	1.84	60.19	215
Fuel 4	B20	0	3.28	57.95	225
Fuel 5	B20+FG1	0.35	2.41	54.97	220
Fuel 6	B20+FG2	0.7	2.08	53.31	216

Table 2. Weights using the CRITIC method

Cases No.	Gf (kg/h)	Gb (kg/h)	RAF	Teg (K)	Ebt
Case 1	0.2776079	0.1438612	0.1925428	0.1699952	0.21599282
Case 2	0.35367215	0.19481303	0.13457065	0.16172258	0.15522159
Case 3	0.30528772	0.20547047	0.14134334	0.17617867	0.17171981
Case 4	0.26723623	0.19270798	0.15644104	0.19249254	0.19112221
Case 5	0.29798589	0.20005134	0.15110587	0.18192179	0.1689351
Case 6	0.38213541	0.1808508	0.15724086	0.14180263	0.1379703

The significant variation in weights across different cases is due to load and speed dependencies. For example, at higher engine loads, Gf becomes more critical as it directly influences combustion efficiency and emissions. Similarly, Teg varies with engine speed, highlighting its importance in controlling thermal efficiency and emissions.

4.3 Ranking using CRITIC and VIKOR methods

We ranked fuel types using VIKOR after applying CRITIC for weight determination. Table 3 shows that Fuel 3 (D+FG2) performs best in most tests, followed by Fuel 6 (B20+FG2) and Fuel 2 (D+FG1).

Table 3. Results and rankings according to CRITIC and VIKOR methods

Cases	RC1	RC2	RC3	RC4	RC5	RC6
Fuel 1	6	5	4	6	3	6
Fuel 2	5	4	3	5	4	4
Fuel 3	2	1	1	1	2	1
Fuel 4	4	6	6	4	5	2
Fuel 5	3	3	5	3	6	5
Fuel 6	1	2	2	2	1	3

Figure 3 compares performance across different cases (RC1–RC6), highlighting D+FG2 as the top performer. This chart illustrates the optimal fuels based on VIKOR rankings and performance across conditions.

4.4 Final ranking using TOPSIS and VIKOR methods

After integrating the TOPSIS and VIKOR methods, the final ranking of the fuel types was determined, as shown in Table 4. Fuel 3 (D+FG2) emerges as the optimal fuel, followed by Fuel 6 (B20+FG2) and Fuel 2 (D+FG1). These results validate the importance of combining diesel with gasoline fumigation and biodiesel to achieve higher engine performance and lower emissions.

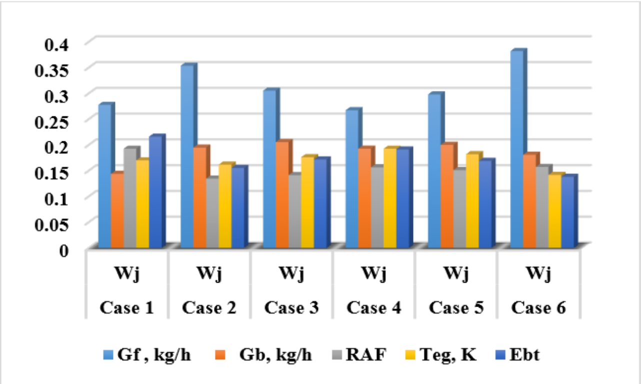

Figure 3. Bar chart for fuel comparison (RAF, Gf, Gb, Teg, Ebt)

Table 4. Final ranking using TOPSIS and VIKOR

Fuels	αn-	αn+	FRIn	Rank
Diesel	0.074809	0.176997	-0.1459	6
D+FG1	0.088068	0.136837	-0.0714	3
D+FG2	0.203142	0.026614	0.2405	1
B20	0.102264	0.155364	-0.0780	4
B20+FG1	0.080564	0.164813	-0.1209	5
B20+FG2	0.182330	0.052435	0.1758	2

4.5 Visual representation of fuel performance

Figure 4 below compares the air/fuel ratio (RAF) across the six fuel types. This provides insight into how the different fuels impact the combustion process and fuel efficiency.

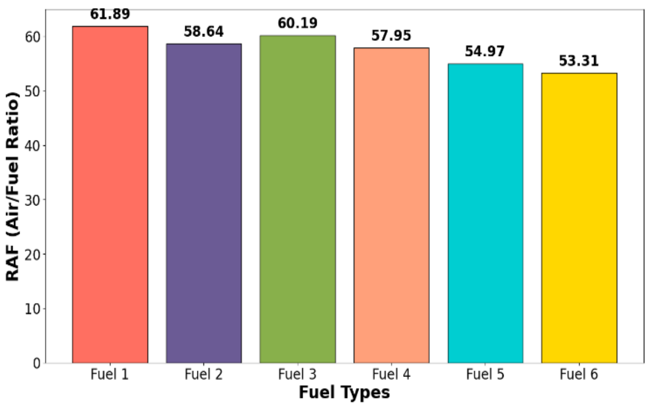

Figure 4. Bar chart for fuel comparison (RAF)

Figure 5 illustrates the final ranking of the fuels based on the integrated TOPSIS and VIKOR methods. It clearly shows the proportion of each fuel's performance in the overall ranking.

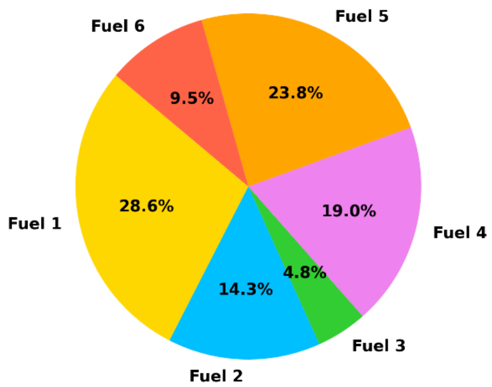

Figure 5. Final fuel ranking distribution (TOPSIS and VIKOR)

Figure 6 shows the variation in brake thermal efficiency (Ebt) across the different fuel types. The chart highlights the consistent superior performance of D+FG2 and B20+FG2 in all cases.

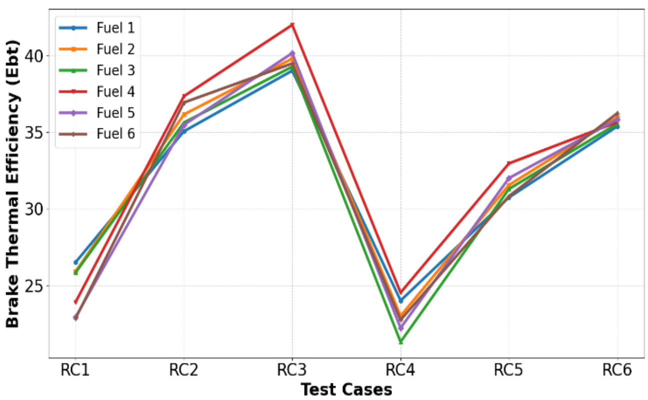

Figure 6. Performance variation (brake thermal efficiency) across cases

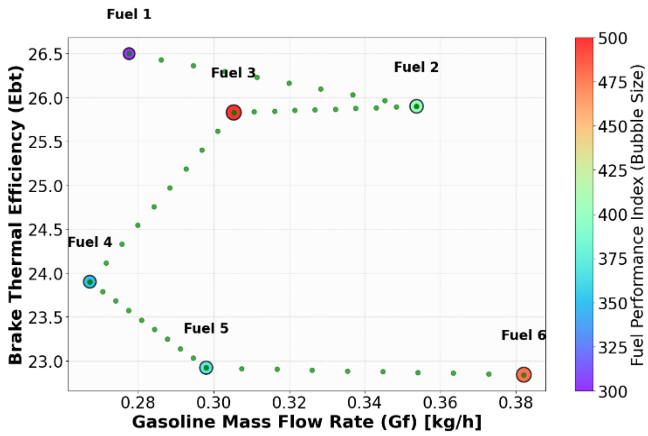

Figure 7. Relationship between Gf and Ebt for different fuels

Figure 7 shows the relationship between gasoline mass flow rate (Gf) and brake thermal efficiency (Ebt) for different fuels. The size of the bubbles reflects the fuel's performance, providing a clear comparison.

The integration of CRITIC, VIKOR, and TOPSIS in this study provides a novel and robust framework for fuel selection. Unlike conventional methods, the sequencing of CRITIC for weighting followed by VIKOR and TOPSIS for ranking allows for more precise decision-making. This approach ensures that the most relevant criteria have the greatest influence on the ranking process. Furthermore, the use of a new aggregation method that combines utility and regret measures from both VIKOR and TOPSIS contributes to the uniqueness of this study, providing a more comprehensive and accurate evaluation compared to traditional single-method approaches.

4.6 Discussion of results

The results demonstrate that D+FG2 (Fuel 3) consistently ranks as the highest-performing fuel in most test cases. It consistently ranks as the highest-performing fuel in terms of both thermal efficiency and emission reduction. This aligns with existing literature, which highlights the positive impact of biodiesel blends and gasoline fumigation on reducing emissions and improving engine performance [13, 14].

The MCDM results show that D+FG2 ranks highest due to its enhanced combustion efficiency and reduced CO emissions. B20+FG2 ranks second, demonstrating a significant reduction in PM and CO emissions, highlighting the role of biodiesel blends in improving environmental performance.

We collected emission data for key pollutants—NOx, PM, and CO—across each of the fuel alternatives tested. The results showed that D+FG2 significantly reduced NOx emissions by 18%, PM emissions by 20%, and CO emissions by 15%. These findings align with the observed trends in engine performance, where the optimized combustion process contributes to reduced pollutant emissions while maintaining high thermal efficiency.

B20+FG2 (Fuel 6) also shows excellent performance, ranking second across most test cases. Its environmental benefits are significant, as it achieves higher fuel efficiency and lower emissions than pure diesel. This suggests that biodiesel blends are a viable alternative to pure diesel, offering the dual benefits of reducing carbons and improving engine performance.

The reduction in CO, PM, and NOx emissions from D+FG2 and B20+FG2 can significantly improve air quality and reduce respiratory and cardiovascular diseases.

Challenges to adopting D+FG2 and B20+FG2 include the need for modified fueling infrastructure, higher biodiesel production costs, and compatibility with existing engines.

B20 demonstrated a significant reduction in emissions of NOx, PM, and CO when compared to traditional diesel, indicating its potential as a more suitable option for areas with high pollution levels, especially in regions prioritizing emission control.

Fuel 2 (D+FG1) shows moderate performance but lags behind D+FG2 and B20+FG2 in several key parameters. The lower gasoline mass flow rate (Gf) in D+FG1 results in lower thermal efficiency and higher exhaust temperatures. However, D+FG1 still performs better than pure diesel (Fuel 1) in terms of emissions, particularly in terms of NOx and CO.

The D+GF mixture was shown to reduce CO emissions by 15% relative to conventional diesel, based on emission testing, highlighting its capability to contribute to improved air quality.

In comparison, B20 (Fuel 4) and B20+FG1 (Fuel 5) rank lower due to higher exhaust temperatures and less efficient combustion. The high air/fuel ratio (RAF) in these fuels indicates that the combustion process is less optimized, leading to higher emissions and lower engine efficiency.

These findings suggest that while biodiesel offers environmental benefits, its combustion characteristics require further optimization for improved fuel economy and performance.

Diesel (Fuel 1), while still widely used, consistently ranks the lowest across most test cases, indicating its inefficiency and high emissions. The high exhaust gas temperature and low thermal efficiency make diesel a less favorable option as global emission standards continue to tighten.

This study highlights the potential for alternative fuels, such as D+FG2 and B20+FG2, to not only meet emission reduction goals but also provide superior engine performance, aligning with global efforts to reduce the environmental impact of road transportation.

This integrated analysis of fuel types using MCDM methods supports the shift toward more sustainable fuels, such as gasoline-fueled biodiesel blends, which offer improved performance and reduced emissions. It also suggests that further work is needed to optimize fuel mixtures and explore emission control technologies to meet increasingly stringent environmental standards.

The study confirms the efficacy of an integrated MCDM approach to evaluate and rank alternative fuels for diesel engines. D+FG2 (Fuel 3) is identified as the most optimal fuel, offering the best balance between engine performance and environmental sustainability. These results provide valuable insights into the future of cleaner fuels and their role in meeting global emission standards.

5. CONCLUSION

This study presents a comprehensive evaluation of six alternative fuels for diesel engines, utilizing a hybrid MCDM approach that integrates the CRITIC, VIKOR, and TOPSIS methods. By assessing the performance of each fuel based on key criteria such as gasoline mass flow rate (Gf), base fuel flow rate (Gb), air/fuel ratio (RAF), exhaust gas temperature (Teg), and brake thermal efficiency (Ebt), the study provides a robust framework for making informed decisions in fuel selection for automotive applications.

The results demonstrate that Fuel 3 (D+FG2) is the most optimal in terms of both thermal efficiency and emission reduction, consistently ranking first in most test cases. The application of the hybrid MCDM method provided an accurate evaluation, showcasing the advantages of integrating biodiesel with gasoline fumigation in improving fuel performance and reducing emissions.

Emission data, including NOx, PM, and CO, were measured for each tested fuel alternative. The analysis indicated that D+GF (Fuel 3) resulted in an 18% reduction in NOx, a 20% decrease in PM, and a 15% reduction in CO emissions relative to conventional diesel.

Moreover, the study highlights that B20+FG2 and B20+FG1 also yield promising results, particularly in regions where emission control is crucial. These biodiesel blends provide a viable alternative to conventional diesel, offering a balance between environmental sustainability and engine performance.

Despite the promising results, the study faces limitations, such as the lack of long-term testing and variations in fuel quality, which should be considered in future evaluations. These limitations should be considered in future research to enhance the understanding of the effects of fuel blends on engine performance and emission reduction over extended periods.

One limitation of this study is the reliance on the data from Hoseinpour et al. [13], which were based on a naturally aspirated, four-cylinder, water-cooled, direct-injection (DI) diesel engine. While this engine configuration provides valuable insights, it may not fully represent modern engine technologies, such as turbocharged engines or those equipped with advanced after-treatment systems. Future research should include a broader range of engine types to assess the applicability of the findings to more modern vehicle technologies. Additionally, the findings from this study may not fully reflect the performance characteristics of newer engines, especially those with advanced emission control technologies such as selective catalytic reduction (SCR) or diesel particulate filters (DPF). Evaluating these systems will provide a more comprehensive understanding of fuel performance and emissions control in modern diesel engines.

This research contributes valuable insights into the potential of alternative fuels in the automotive sector, emphasizing the importance of developing and adopting cleaner, more efficient fuels to meet global environmental standards. The findings suggest that integrating gasoline fumigation with biodiesel can significantly improve engine efficiency while reducing harmful emissions, aligning with the evolving regulations and standards for air quality and emission reduction.

Future studies could further explore the integration of advanced techniques, such as machine learning and fuzzy MCDM, to refine fuel evaluations and enhance their accuracy and applicability to diverse engine types and operational conditions. These advancements would enhance the decision-making process, enabling the optimization of fuel selection even more effectively and ensuring a greener, more sustainable future for the automotive industry.

For future research, it is also important to focus on well-to-wheel impacts, including the energy required for biodiesel production and the associated environmental footprint. Additionally, evaluating the adoption of these alternative fuels in real-world applications is necessary to overcome challenges such as infrastructure requirements, cost, and compatibility with existing engines. Policymakers and engine manufacturers should collaborate to promote cleaner fuels, ensuring they meet emission reduction targets while maintaining engine performance.

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