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Article

Investigation on performance of ethanol-diesel blends in CI engine using fuzzy AHP-TOPSIS

Kalyan Mukherjee[1*], Pritam Bhattacharjee[1], Manik Chandra Das[2]

[1]Department of Automobile Engineering, Dr. Sudhir Chandra Sur Institute of Technology and Sports Complex, Dum Dum, India
[2]Department of Industrial Engineering and Management, Maulana Abul Kalam Azad University of Technology, West Bengal, India
*Correspondence: kalyan.aue08@gmail.com

Abstract: The increasing demand for energy due to industrial growth and urbanisation has led to a surge in petroleum-based fuel consumption, prompting researchers to explore alternative energy sources, with ethanol-diesel mixtures identified as a critical variable for producing a more effective, harmonic, and less polluting alternative fuel for automobiles. The present research employs the hybrid Multi-Criteria Decision-Making (MCDM) technique called Fuzzy Analytic Hierarchy Process (FAHP) and Technique for Order of Preference by Similarity to an Ideal Solution (TOPSIS) to rank ethanol-diesel mixtures based on diesel engine performance under various load conditions. In order to acquire data, the different ethanol-diesel combinations were generated by the addition of 5%, 8%, 10%, and 12% ethanol in diesel and tested in a 4-stroke inline 4-cylinder liquid-cooled diesel engine under 5 kg, 10 kg, 15 kg, and 20 kg loads, respectively. The ethanol-diesel combinations were ranked using four criteria: brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), exhaust gas temperature (EGT), and total fuel consumption (TFC). The FAHP-TOPSIS approach determined the relative importance of each criterion, with BTE ranking as the top weighted criterion, with a 10% ethanol and 90% diesel blend at 20 kg load as the optimum alternative.
Keywords: Ethanol, Diesel Engine, Engine Performance, FAHP, TOPSIS

1. Introduction

Several challenges concerning higher energy requirements, an uncertain supply of oil, a corresponding rise in petroleum costs, and the challenges attributed to air pollution emanating from the consumption of petroleum-based fuels, interest in alternative and environmentally sensitive fuels has blossomed. Engines powered by diesel have extensive applications across an assortment of industrial fields on account of their impressive efficiency [1]. Diesel-powered engines possess an extensive variety of applications in agriculture, manufacturing, and transport owing to their resilient architecture as well as their superior fuel effectiveness [2]. Consequently, it has supplanted conventional sources of power for immense mechanically powered devices such as automobiles and shipping [3]. Nevertheless, the diesel engine releases considerable quantities of particulate matter (PM), hydrocarbons (HC), nitrogen oxides (NOx), and sulphur oxides (SOx), along with other conceivably hazardous and potentially dangerous substances [4], posing an imminent danger to both human wellness as well as the surrounding ecosystem [5]. The consumption of renewable fuel is a successful approach to mitigating emission levels in diesel-powered engines [6]. Fuels with substances like alcohol have the potential to lessen reliance on oil and diesel engine exhaust emissions [7]. In light of their liquid-state form and elevated quantity of oxygen, alcoholic substances could be beneficial for diesel fuel stimulation [8].

Low-carbon alcohols (alcohols with a maximum of three carbon atoms), such as methanol and ethanol, have drawn plenty of attention in recent years as a substance in diesel fuel blends because of their advanced production methods and high oxygen concentration [9–10], which may greatly enhance combustion performance and reduce exhaust emissions [11]. Low-cetane alcohols have the potential to be employed as an alternative fuel source for diesel engines, yet their intended usage is substantially hindered by their large latent heat vaporisation and lower cetane number, coupled with durability and incompatibility concerns [12]. While being employed as diesel fuel substances, high-carbon alcohols with almost as many as four carbons could provide a competitive advantage over low-carbon alcohols. They burn more effectively while possessing greater cetane numbers than low-carbon alcohols. Due to the fact that they possess enhanced miscibility, they can be successfully incorporated into diesel fuel, notably at high blending ratios.

In response to its ability to be recycled as well as its elevated oxygen content as a diesel fuel, supplementary ethanol is one of the most widely employed alcohols. Since ethanol has a greater oxygen content, combustion is improved, and emissions are reduced [13]. Diesel engines are unable to operate on ethanol alone, yet they are capable of running on ethanol-diesel fuel mixes. Ethanol provides various enticing qualities that make it acceptable as a fuel in diesel engines [14], including minimal viscosity, substantial oxygen content, a significant H/C ratio, inadequate sulphur content, and ample evaporative cooling, which boosts volumetric efficiency. When ethanol has been combined with diesel, the consequently diminished viscosity facilitates both the atomization method of fuel surged onto cylinders and enhanced mixing with air. In recognition of ethanol's significant latent heat of evaporation and its ability to provide cooling through evaporation during the intake and compression strokes of a diesel engine, ethanol might possibly be utilized to enhance volumetric efficiency by mixing with diesel or biodiesel fuel. Ethanol has the possibility of being employed in three different ways in diesel engines [15-16]. The first method entails injecting ethanol into the air that comes in through an injector installed within the manifold. The second way necessitates manually altering the engine's cylinder head as well as changing the system's settings for the purpose of mounting a dual injection system onto it. Ultimately, ethanol may be effectively used in diesel engines by blending it with diesel fuel, thereby preventing the occurrence of phase separation and ensuring no adverse effects on the engine system. A thorough investigation has been conducted to determine the most effective technique for the approaches indicated above. An investigation performed by Rakopoulos et al. [15] investigated the impact of different ethanol-diesel mixtures on the performance of a 2000 rpm direct injection (DI) diesel engine working under four distinctive loads. The combinations substantially decreased CO and smoke emissions but had a limited impact on NOx emissions. On the flip side, higher increases in both BTE and BSFC were found when the ethanol level in the mixtures rose. Ajav et al. [17] evaluated the consequences of ethanol additions to diesel fuel by volume at 5%, 10%, 15%, and 20% in a diesel engine running at a steady speed and discovered that the addition of ethanol blends raised BSFC while lowering NOx and CO emissions considerably without substantially lowering power. He et al. [18] examined the findings of an experiment wherein ethanol 10% and 30% were combined with diesel fuel in a 4-cylinder DI diesel engine. The use of ethanol blends lessens NOx, CO, and smoke while raising HC emissions. In an experiment carried out by Sayin [14], ethanol-diesel blends containing 10% and 15% ethanol by volume were used. The investigation included running an engine at a load of 30 Nm with engine speeds of 1000 rpm and 1800 rpm. The experiment findings demonstrated that although NOx and BSFC exhibited an increase, CO, HC, and the opacity of smoke observed a reduction. Li et al. [19] analysed the operational and pollution aspects of the engine by considering rated and maximum engine speeds and five distinct engine load circumstances (25%, 50%, 75%, 90%, and 100%). They deployed a single-cylinder DI diesel engine to introduce diesel fuel mixed with varying quantities of ethanol by volume: 5%, 10%, 15%, and 20%. The introduction of ethanol led to a reduction in CO and NOx emissions, as well as an increase in HC and BSFC. In order to demonstrate the detrimental effects of ethanol, Di et al. [20] added it to diesel and biodiesel. The samples of fuel comprised 2, 4, 6, and 8% by volume of ethanol, respectively. Based on reports, when ethanol concentrations got higher, the BTE got better, HC and CO levels dropped, but the concentrations of NOx surged. Huang et al. [21] performed an experiment with the inclusion of 0, 10, 20, 25, and 30% ethanol by volume in diesel. As a consequence, they discovered that the BTE was dropped owing to the diminished heating value of ethanol, which was inadequate, and the formation of smoke was minimised. Alptekin [22] studied the consequences of a fuel combination of 15% ethanol and 85% diesel under three distinct engine speed ranges from 1500 rpm to 2500 rpm with 500 intervals and varied load conditions and discovered that emission levels of pollutants and BSFC grew significantly. In consequence of ethanol's greater oxygen mass concentration as well as a lesser carbon-hydrogen proportion (C/H), Labeckas et al. [23] found that it decreases smoke, CO, and sulphur dioxide (SO2) emissions.

Various methods can be used for anticipating and evaluating the potential applications of alternate energy sources. A wide range of variables need to be addressed by those who make decisions in such a context. MCDM addresses are critical tools for decision-making [24] for separating as well as assessing alternatives in conjunction with criteria [25]. The majority of the most prevalent approaches employed for MCDM are PROMETEE, WSM, ANP, WPM, ELECTRE, TOPSIS, and AHP amongst others [24]. MCDM assessments have previously been employed on a variety of difficulties, notably the assessment of national and international policies regarding energy and the selection of technological advances [26-27], assignments [28], resources [29-30], engineering for security [31], and energy strategic planning [32].

In the past few years, it has also been applied in the automobile industry to find the best appropriate fuel category, fuel-producing technique, and optimal fuel combination for engines. Kumar et al. [33] implemented a FAHP strategy to determine the simplest and most efficient biodiesel manufacturing technique by considering emission characteristics, viscosity, acid value, glycerol segregation, sulphur content, transformation, and expenditure parameters. Sehatpour et al. [34] utilised a MCDM technique to determine the most effective fuel by considering technical, social, regulatory, and financial variables. In another experiment, hybrid MCDM techniques (SWARA and MULTIMOORA) were utilised to determine the ideal fuel alternative among diesel, animal fat biodiesel, vegetable oil biodiesel, and blend fuels [35]. Moreover, Martinez [36] applied the OCRA technique in an investigation aimed at determining the best-suited one among a total of seven fuels that must be gasified prior to deployment to operate a reactor by considering six criteria. Another study [37] adopted the MCDM approach to look into the best conditions for biodiesel application with respect to ideal performance and emission levels in a diesel engine. Consequently, the most effective combination of fuels has been found to be 10% biodiesel and 90% diesel. The MCDM technique was employed in another experiment [38] with the purpose of finding a blend percentage that gives the optimum degree of performance with reduced exhaust emissions among the numerous biodiesel and diesel blends in variable proportions. The COPRAS technique was utilised for this and to determine the most ideal blended fuel based on the optimal findings, which encompassed B5 (5% biodiesel + 95% diesel). Sakthivel et al. [39] adopted TOPSIS and VIKOR, which are MCDM methods that were employed for selecting the combinations. As stated by Sivaraja, C.M., et al. [40], biodiesel mixtures in IC engines could have been selected by employing a hybrid MCDM strategy. In order to determine the most suitable mixture, the following approaches have been employed: FAHP-VIKOR, FAHPTOPSIS, and FAHP-ELECTRE. Furthermore, the outcomes of multiple MCDM techniques are compared.

At present, there is insufficient evidence of investigations that address the decision-making process of a suitable ethanol-diesel fuel blend by considering characteristics related to performance and making use of the MCDM technique in the available literature. As a consequence, a hybrid MCDM approach termed FAHP paired with TOPSIS has been suggested for analysing and determining the most suitable mixture for a CI engine operated under four distinct loads to achieve maximum thermal efficiency while simultaneously limiting fuel consumption and thermal energy loss.

2. Materials and Methods

In the present research, a hybrid MCDM strategy referred to as FAHP in combination with TOPSIS was implemented to analyse and select the most suitable blend for a diesel engine that executes operations over a total of four distinct loads: 5 kg, 10 kg, 15 kg, and 20 kg at steady engine rpm, with the aim being to achieve the maximum thermal efficiency while decreasing fuel consumption and the amount of thermal energy loss. In order to achieve the aforementioned objectives, four different mixtures were considered: 5% ethanol and 95% diesel (D95E5), 8% ethanol and 92% diesel (D92E8), 10% ethanol and 90% diesel (D90E10), and 12% ethanol and 88% diesel (D88E12).

2.1 Blend Preparation

While mixing ethanol with diesel fuel, it must be precise to prevent separation of the phases. During the formation of the mixture, no phase separation was observed in the test fuels of ethanol when mixed with diesel fuel at various percentages (5%, 8%, 10%, and 12% by volume). According to Hansen et al. [41], the process of phase segregation of a diesel-ethanol mixture cannot take place when the ambient air temperature exceeds 100C. In the study by Lapuerta et al. [42], phase separation commenced as the ambient temperature ultimately went below 100C. In the original experiment, the test fuels had been blended at 320C and maintained at approximately 360C right through testing. Table 1 shows the properties of the test fuels.

Table 1: Properties of Test Fuels

Sl No.	Test fuels	Specific gravity at 32◦C	Calorific value (KJ/kg)
1	5% E + 95% D (D95E5)	0.835	43631.8
2	8% E + 92% D (D92E8)	0.834	43300.0
3	10% E + 90% D (D90E10)	0.833	43192.5
4	12% E + 88% D (D88E12)	0.830	42900.0

2.2 *Method*

2.2.1 **Experimental set up**

A four-cylinder four-stroke inline 1500 cc water-cooled diesel engine with rope brake dynamometer was utilised for this test. The detailed specifications of the engine are shown in the Table 2.

Table 2: Engine Specification

Engine Parameters	Unit	Specification
Engine Type	-	Inline 4 Cylinder, 4 Stroke, Water Cooled Diesel Engine
Power Output	HP	10
Engine Speed	rpm	1500
Cylinder Number	-	4
Cooling Medium	-	Water Cooled
Bore x Stroke	mm	75 x 79
Displacement	cc	1500
Arm Length	mm	200
Orifice Diameter	mm	30
Valves per cylinder	-	2

The engine was outfitted with devices that measured fuel usage and speed. An aperture for monitoring the consumption of air was set up in the air box, which fed the engine with air. The variation in pressure across the two ends of the orifice was determined using a pressure variation metre. The airbox was equipped with a conventional, sharp-edged opening that allowed monitoring of the intake air that was utilised by the engine. The size of the orifice opening was calculated at 30 mm. The fuel absorption rate had been measured by a glass burette and timer. The speed of the engine was being observed with a computerised tachometer. Prior to obtaining any readings, the engine was warmed up. The examination and data recording had begun when it attained its state of stability. Engine was run on ethanol blends of 5, 8, 10, and 12% by volume with diesel oil. The engine was loaded with 4 distinct loads comprising 5, 10, 15, and 20 kg for each running condition, with the engine speed fixed at 1500 rpm. The tests were performed without any alteration in engine. The experimental circumstances are outlined in Table 3.

Table 3: Test Condition

Parameters	Unit	Condition
Engine Speed	rpm	1500
Engine Load	kg	5, 10, 15 and 20
Manometric difference	cm	and 8.2

2.2.2 Fuzzy AHP

The Analytic Hierarchy Process (AHP) is combined with fuzzy concepts in the FAHP decision-making process. The AHP approach is a multi-criteria decision-making method that employs pairwise contrasts to establish the relative significance of criteria. Fuzzy set theory is a mathematical method that addresses uncertainty and imprecision.

The method of operation of this strategy is outlined below.

Step 1: Construct a matrix of pairwise comparisons that takes into account the viewpoints of linguistic experts, as demonstrated in the data table below [43].

Definition	Fuzzy triangular scale
Equally important	(1, 1, 1)

Weakly important	(2, 3, 4)
Fairly important	(4, 5, 6)
Strongly important	(6, 7, 8)
Absolutely important	(9, 9, 9)
The intermittent values between two adjacent scales	(1, 2, 3)

$$\text{PWCM} = [a_{ij}]_{nxn} = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ C_1 & 1 & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ C_2 & (l_{21}, m_{21}, u_{21}) & 1 & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ C_n & (l_{n1}, m_{n2}, u_{n2}) & (l_{12}, m_{12}, u_{12}) & \cdots & 1 \end{matrix} \quad (1)$$

$$= \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ C_1 & 1 & P_{12} & \cdots & P_{1n} \\ C_2 & P_{21} & 1 & \cdots & P_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ C_n & P_{n1} & P_{n2} & \cdots & 1 \end{matrix} \quad (2)$$

Step 2: Applying the subsequent formula, determine the geometric mean of fuzzy comparison results for each of the criterion

$$\text{GM} = (\prod_{j=1}^{n} P_{ij})^{1/n} \quad (3)$$

$$= (\sqrt[n]{l_1 * l_2 * l_3 * \ldots l_n}, \sqrt[n]{m_1 * m_2 * m_3 * \ldots m_n}, \sqrt[n]{u_1 * u_2 * u_3 * \ldots u_n}) \quad (4)$$

Step 3: Applying the equation provided below, calculate the corresponding fuzzy weights for each of the circumstances

$$W_F = (l_i * \sum u_i^{-1}, m_i * \sum m_i^{-1}, u_i * \sum l_i^{-1}) \quad (5)$$

Step 4: Applying the equation down below, determine the corresponding non-fuzzy weight (w) of each criterion

$$W = \frac{l_i + m_i + u_i}{3} \quad (6)$$

Step 5: Determine the normalized weights (N) of each criterion employing the formula provided down below, and subsequently rank the corresponding criterion

$$W_N = \frac{w_i}{\sum w} \quad (7)$$

2.2.3 TOPSIS

In 1981, Hwang and Yoon introduced a technique for order preference by similarity to ideal solution (TOPSIS). The variation among both positive and negative optimal solutions can be determined by applying this approach. The various steps of TOPSIS method are outlined below.

Step 1: After conducting the experiment in a controlled environment, the following data matrix has been formed. In the matrix, alternatives are placed in the rows, and the performance of the alternatives against the individual criteria is shown in the column.

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdot & \cdot & a_{1m} \\ a_{21} & a_{22} & \cdot & \cdot & a_{2m} \\ \cdots & \cdot & \cdot & \cdot & \cdot \\ \cdots & \cdot & \cdot & \cdot & \cdot \\ a_{q1} & a_{q2} & \cdot & \cdots & a_{qm} \end{bmatrix} \quad (8)$$

Step 2: The square of each individual a_{ij} value is determined, as well as normalized readings can be obtained by employing the equation (9). N is a standardized matrix structure which is generated.

$$N_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{q} a_{ij}^2}} \tag{9}$$

$$N_{ij} = \begin{bmatrix} n_{11} & \cdot & \cdot & \cdot & a_{1m} \\ n_{21} & \cdot & \cdot & \cdot & n_{2m} \\ \cdots & \cdot & \cdot & \cdot & \cdot \\ \cdots & \cdot & \cdot & \cdot & \cdot \\ n_{q1} & \cdot & \cdot & \cdots & n_{qm} \end{bmatrix} \tag{10}$$

Step 3: FAHP weight computations were carried out with the goal of developing a weighted, normalised decision-making matrix. The matrix with U components has been widely assumed to be $u_{ij} = n_{ij}$ w

$$U_{ij} = \begin{bmatrix} n_{11}w_1 & n_{12}w_2 & \cdot & \cdot & n_{1m}w_m \\ n_{21}w_1 & n_{22}w_2 & \cdot & \cdot & n_{2m}w_m \\ \cdots & \cdot & \cdot & \cdot & \cdot \\ \cdots & \cdot & \cdot & \cdot & \cdot \\ n_{q1}w_1 & \cdot & \cdot & \cdots & n_{qm}w_m \end{bmatrix} \tag{11}$$

Step 4: Identifying positive and negative ideal solutions:

Negative possibilities for optimal values:

$$A^- = \{(min\, u_{ij} | \, j\epsilon J), (max\, u_{ij} | \, j\epsilon J') | \, i = 1, 2, \dots m\} \rightarrow A^- = \{u_1^-,\, u_2^-,\, \cdots\cdots u_m^-\} \tag{12}$$

Positive possibilities for optimal values:

$$A^+ = \{(max\, u_{ij} | \, j\epsilon J), (min\, u_{ij} | \, j\epsilon J') | \, i = 1,2, \dots m\} \rightarrow A^+ = \{u_1^+, u_2^+, \cdots\cdots u_m^+\} \tag{13}$$

Step 5: Calculating values for both negative ideal (S_i^-) as well as positive ideal (S_i^+) distances:

$$S_i^- = \sqrt{\sum_{j=1}^{m} (U_{ij} - U_j^-)^2} \tag{14}$$

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(U_{ij} + U_j^+\right)^2} \tag{15}$$

Step 6: C_i^*(relative proximity to ideal solving solution) is calculated using equation (16) and ideal and non-ideal point spacing.

$$C_i^* = \frac{S_i^-}{S_i^- - S_i^+} \tag{16}$$

3. Application of Proposed Method

3.1 Determination of Criteria Weight using FAHP

There are four criteria (BSFC, BTE, EGT, and TFC) are used to assess the performance of four fuel combinations. Table 4 offers a short summary of the criteria. BTE is the most beneficial among the four criteria, with a higher value signifying better results. The remaining three criteria are non-beneficial.

Table 4: List of Criteria

Criteria	Brief description
TFC (C1)	Total fuel consumption describes the total quantity of fuel consumed by an engine during a certain timeframe or variety of operational circumstances. This indicator is critical in assessing an engine's effectiveness and capabilities, providing information regarding fuel economy, overall performance, and ecological ramifications.
BSFC (C2)	BSFC is a fuel efficiency metric that is used by engines with internal combustion. It specifies the quantity of fuel used by an engine in order to generate one unit of power.

BTE (C3)	The ratio of the amount of brake power generated to the amount of heat supplied is commonly referred to as the BTE. It represents the relationship between the heat energy of the fuel and engine brake power.
EGT (C4)	The temperature of exhaust gases in an IC engine's exhaust system is referred to as EGT. Since the temperature of the exhaust gas varies depending on the fuel/air combination getting into the cylinders, it could potentially be used for regulating the engine's fuel/air mixture.

Table 5: Form pairwise comparison matrix using linguistic terms

Criteria	C1	C2	C3	C4
C1	1	1	1	0.5
C2	4	3	2	1
C3	4	3	2	8
C4	8	7	6	0.25

Table 6: Determine the geometric mean of fuzzy comparison values with summation, reciprocal

Criteria	Fuzzy Geometric means
C1	0.4518
C2	1.0746
C3	2.8284
C4	0.8409
Sum	5.1957
Reciprocal	0.1925
Inverse order	0.1986

Table 7: Determine the relative fuzzy weights

Criteria	Fuzzy weight
C1	0.0897
C2	0.2134
C3	0.5616
C4	0.1670

Table 8: Determine the relative non-fuzzy weight (w) and normalized weights (N) with corresponding ranking

Criteria	Non-fuzzy Weight (w)	Normalized weights (N)	Rank
C1	0.0718	0.0718	4
C2	0.2039	0.2038	2
C3	0.5375	0.5373	1
C4	0.1871	0.1871	3

Sum	1.0003	1.0000	

3.2 Performance Evaluation using TOPSIS

Four fuel blends, D88E12, D90E10, D92E8, and D95E5, have been selected as alternatives under the four different loads of 5 kg, 10 kg, 15 kg, and 20 kg, respectively, in order to assess and rank them under different engine loads. Table 9 displays their performance in relation to the defined criteria. The elements in Table 9 are normalized employing equation (9) as shown in Table 10. Table 11 provides the values of the weighted normalised matrix as calculated by equation (11). Equations (12) and (13) were used to calculate negative and positive ideal solution values, which are shown in Table (12). The distance matrix has been generated for each alternative using the step 5 of TOPSIS method. Equation (16) determines the ultimate rank of the alternatives. Table 13 displays the comparative ranking and FAHP-TOPSIS performance rating of the available alternatives.

Table 9: Engine performance evaluation of test fuels for different loads

Alternatives		**Criteria**			
Loads (kg)	**Fuels**	**C1**	**C2**	**C3**	**C4**
5	D95E5	1.01	0.73	9.66	140
	D92E8	1.112	0.732	9.5	138
	D90E10	1.081	0.742	9.39	133
	D88E12	1.091	0.748	9.28	130
10	D95E5	1.404	0.475	17	167
	D92E8	1.47	0.477	16.4	164
	D90E10	1.363	0.482	16.3	162
	D88E12	1.404	0.485	16.2	160
15	D95E5	1.664	0.36	22.9	196
	D92E8	1.75	0.378	22.5	190
	D90E10	1.748	0.379	22	189
	D88E12	1.716	0.381	21.6	187
20	D95E5	2.004	0.326	25.8	236
	D92E8	2.022	0.328	25.5	233
	D90E10	1.983	0.331	25.3	227
	D88E12	2.025	0.333	25	225

Table 10: Normalized Matrix of Experimental Values

Loads (kg)	**Fuels**	**C1**	**C2**	**C3**	**C4**
5	D95E5	0.15855573	0.361386139	0.124646770	0.191021968
	D92E8	0.17456829	0.362376238	0.122582227	0.188293082
	D90E10	0.16970172	0.367326733	0.121162854	0.181470869
	D88E12	0.17127158	0.370297030	0.119743481	0.177377541
10	D95E5	0.22040816	0.23514851	0.219357669	0.227861918
	D92E8	0.23076923	0.23613861	0.211615634	0.223768591
	D90E10	0.21397174	0.238613861	0.210325295	0.221039705
	D88E12	0.22040816	0.240099010	0.209034955	0.218310820
15	D95E5	0.26122449	0.178217822	0.295487684	0.267430755
	D92E8	0.27472527	0.187128713	0.290326327	0.259244099
	D90E10	0.27441130	0.187623762	0.283874631	0.257879656
	D88E12	0.26938775	0.188613861	0.278713274	0.255150771
20	D95E5	0.31459968	0.161386139	0.332907521	0.322008460

	D92E8	0.31742543	0.162376238	0.329036504	0.317915132
	D90E10	0.31130298	0.163861386	0.326455825	0.309728476
	D88E12	0.31789638	0.164851485	0.322584808	0.30699959

Table 11: Weighted Normalized Decision Matrix

Loads (kg)	Fuels	C1	C2	C3	C4
5	D95E5	0.01138	0.0737	0.0669	0.0357
	D92E8	0.01253	0.0739	0.0659	0.0352
	D90E10	0.01218	0.0749	0.0651	0.0339
	D88E12	0.01229	0.0755	0.0643	0.0332
10	D95E5	0.01583	0.0479	0.1179	0.0426
	D92E8	0.01657	0.0481	0.1137	0.0419
	D90E10	0.01536	0.0486	0.1130	0.0414
	D88E12	0.01583	0.0489	0.1123	0.0408
15	D95E5	0.01876	0.0363	0.1588	0.0500
	D92E8	0.01973	0.0381	0.1559	0.0485
	D90E10	0.01970	0.0382	0.1525	0.0482
	D88E12	0.01934	0.0384	0.1498	0.0477
20	D95E5	0.02259	0.0329	0.1789	0.0602
	D92E8	0.02279	0.0330	0.1768	0.0595
	D90E10	0.02235	0.0334	0.1754	0.0580
	D88E12	0.02282	0.0336	0.1733	0.0574

Table 12: Ideal Solutions

Positive Ideal Solution Values			
C1	**C2**	**C3**	**C4**
0.01138	0.0329	0.1789	0.0332
Negative Ideal Solution Values			
C1	**C2**	**C3**	**C4**
0.02282	0.0755	0.0643	0.0602

Table 13: Positive and negative ideal solutions, relative proximity to ideal solutions, and ranking

Loads (kg)	Fuels	S_i^+	S_i^-	C_i^*	Rank
5	D95E5	0.1192	0.0272	0.186	15
	D92E8	0.1202	0.0271	0.184	16
	D90E10	0.1213	0.0284	0.189	14
	D88E12	0.1223	0.0289	0.191	13
10	D95E5	0.0637	0.0632	0.498	9
	D92E8	0.0677	0.0597	0.469	10
	D90E10	0.0684	0.0592	0.464	11
	D88E12	0.0690	0.0586	0.459	12
15	D95E5	0.0274	0.1029	0.789	5
	D92E8	0.0293	0.0997	0.773	6
	D90E10	0.0319	0.0966	0.752	7
	D88E12	0.0339	0.0941	0.735	8
20	D95E5	0.0292	0.1223	0.8072	4
	D92E8	0.0287	0.1203	0.8074	3
	D90E10	0.0273	0.1188	0.813	1
	D88E12	0.0274	0.1168	0.810	2

4. Result and Discussion

The most strongly designated ranking arrangement has been determined for each of the different ethanol-diesel blends, depending upon the 5, 10, 15, and 20 kg loads, while taking four essential engine performance factors into account. FAHP coupled with TOPSIS computations identified the best alternative compared with the remainder of the alternatives by using a combination of an MCDM approach. Employing FAHP, the authors have evaluated different ethanol-diesel fuel blend engine performance characteristics and developed a paired comparison matrix as shown in Table 5. FAHP is employed in determining the weights of each criterion stipulated by those making the decisions. The geometric mean of fuzzy comparison results for each criterion was obtained using equations (3) and (4). Obtain the relevant fuzzy weights for each of the instances using equation (5). Equations (6) and (7) were employed for obtaining the corresponding non-fuzzy weights and normalised weights associated with every criterion.

Table 8 represents the derived prioritised weight for four separate criteria. The ranked weighted criteria include C3 as the first rank with 53.73% weightage and C2, C4, and C1 as the second, third, and fourth ranks with weightage of 20.38%, 18.71%, and 7.18%, respectively. Table 4 provides a list of criteria and a brief description of each.

The TOPSIS approach is employed to identify the most effective alternative. TOPSIS is computed using several engine performance metrics such as TFC, BSFC, BTE, and EGT of diesel engines operated by different ethanol diesel fuel blends such as D95E5, D92E8, D90E10, and D88E12 under various load conditions ranging from 5 kg to 20 kg at a 5-kg interval. The TOPSIS approach starts off with the establishment of the normalised matrix of outcomes from experiments by applying the equation (9) as given in Table 10. As indicated in Table 11, a weighted normalised matrix was generated in the following phase. In both positive and negative aspects, after constructing a weighted normalised matrix, ideal solutions have been found and presented in Table 12. The Euclidian distance was subsequently calculated by applying equations (14) and (15). Table 13 provides the final performance score calculated employing equation (16). In the end, alternatives are rated based on their overall performance value. The table 13 also includes the rankings for each of the ethanol and diesel fuel mixtures under different engine loads.

Table 14: Notations used for Alternatives

Loads (kg)	Fuels	Notation	Rank
5	D95E5	A1	15
	D92E8	A2	16
	D90E10	A3	14
	D88E12	A4	13
10	D95E5	A5	9
	D92E8	A6	10
	D90E10	A7	11
	D88E12	A8	12
15	D95E5	A9	5
	D92E8	A10	6
	D90E10	A11	7
	D88E12	A12	8
20	D95E5	A13	4
	D92E8	A14	3
	D90E10	A15	1
	D88E12	A16	2

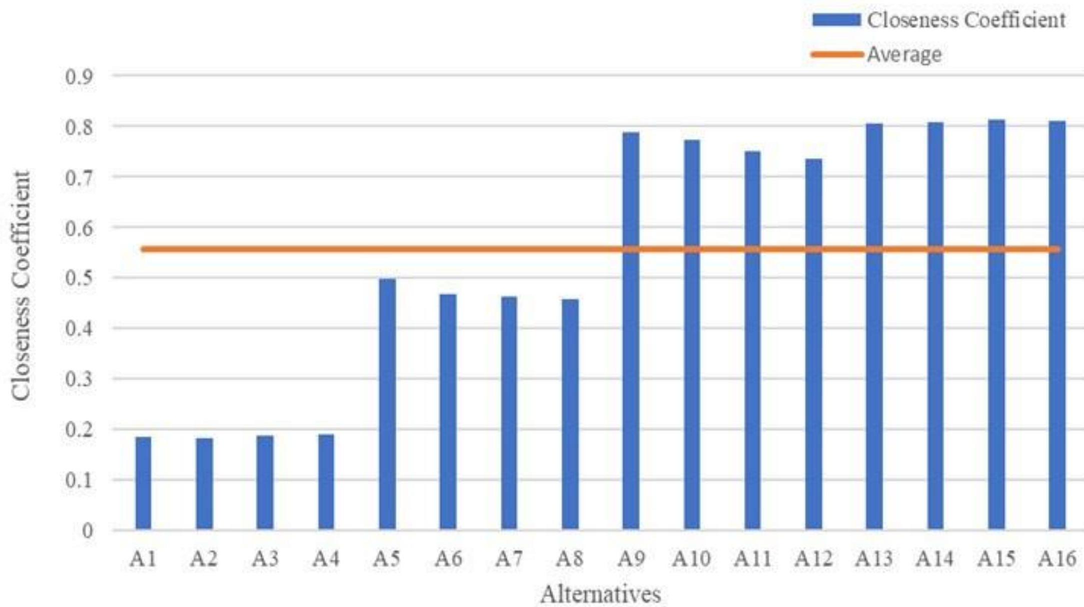

Figure 1: Variation of Alternatives with their Closeness Coefficient values

Table 14 presents the ultimate ranking results for each and every alternative. The results indicated the use of the hybrid MCDM approach known as FAHP paired with TOPSIS-elected A15 as the optimal ethanol-diesel fuel blend across different load conditions. A15 indicates a D90E10 fuel blend with a load of 20 kg. Figure 1 provides a graphical depiction of many different alternatives, presenting their proximity coefficient values and the average value, which is represented by a straight line. Those alternatives with proximity coefficient values greater than the average value are referred to as good performers, while the others are designated as the poor performers.

Figure 1 illustrates that A9 to A16 represent the eight alternatives positioned over the average line. In contrast, the rest of the alternatives are positioned below the average line, indicating that the same fuel blend performs well under higher load conditions but doesn't perform effectively under low load conditions.

4.1 BTE

It can be defined as the ratio of heat stipulated for the engine per unit of time to heat equivalent to brake power per unit of time. Figure 2 illustrates the BTE against engine load at constant speed (1500 rpm). BTE is assessed using BSFC and the calorific value of the fuel. D95E5 fuel blend possesses the maximum BTE under all load conditions because of its relatively low BSFC and elevated energy content. D95E5 exhibited the highest calorific value among all the combinations of fuels employed in the present study since it comprises 95% diesel fuel by volume and 5% ethanol by volume, with diesel containing the maximum calorific value and therefore increasing BTE. The BTE is raised according to increasing loads for every type of fuel blend. It occurs since, as the load increases, the proportion of air to fuel drops, resulting in a dense mixture that delivers more fuel energy for developing more power [44].

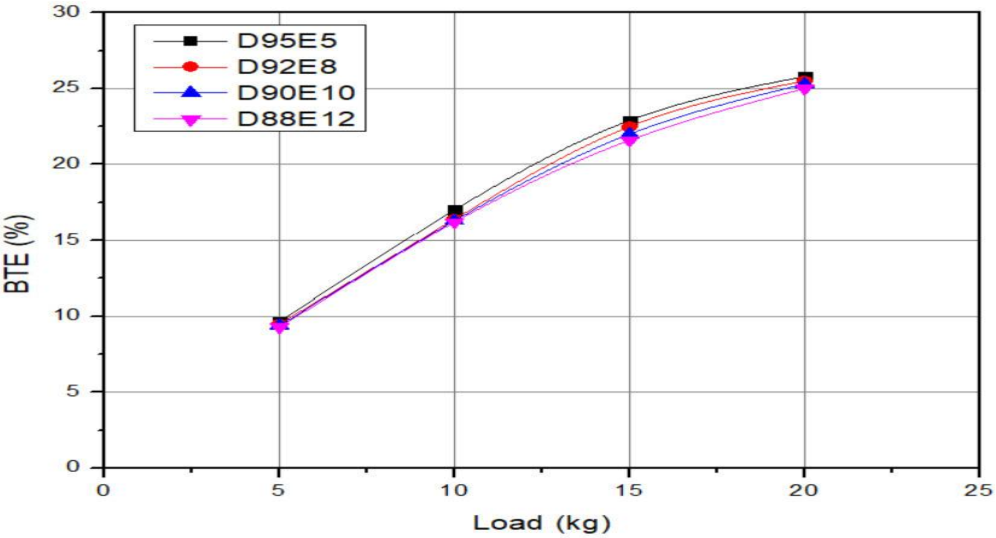

Figure 2: Variation of BTE versus engine loads at 1500 rpm

4.2 BSFC

Across each of the fuel variations, the amount of BSFC drops as the load rises. The amount of BSFC climbed while the ethanol content proportion in the diesel-ethanol combinations increased under various engine loading circumstances. It is a consequence of ethanol having lower heating values than diesel fuel. When ethanol is compared to diesel fuel, it is highly oxygenated. Enhanced BSFC is the outcome of exceptionally oxygen-rich combustion. To obtain the same amount of power produced by fuels having a lower calorific value, like alcohol blends, more fuel needs to be injected. Furthermore, because the cetane number of the alcohols is lower, the alcohol blends' ignition delay duration is longer, therefore the BSFC consequently becomes greater. Since it encompasses 95% diesel fuel by volume and 5% ethanol, the D95E5 fuel blend recorded the lowest BSFC values among the four different fuel combinations employed in the present investigation to produce the same quantity of power. Because the ethanol fuel proportion in this fuel combination is lower, it releases more heat energy than other mixtures with an elevated diesel fuel proportion. For all tested fuels, the amount of BSFC was observed to decline as the load increase. This is owing to a greater percentage increase in brake power with load than an increase in consumption of fuel [45].

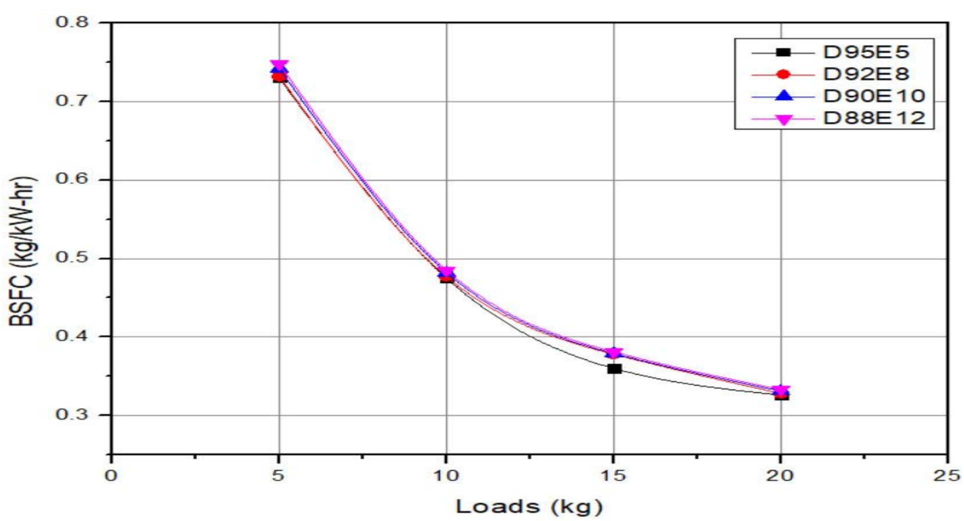

Figure 3: Variation of BSFC versus engine loads at 1500 rpm

4.3 EGT

The EGT illustrates how efficiently a fuel's thermal energy is employed. Thermal dissipation from the tailpipe or a rise in exhaust temperature decreases the conversion of heat energy generated from the fuel to work. EGT with an increase in load across all of the fuel categories depicted in Figure 4 because an additional amount of heat is generated owing to the combustion of additional fuel [46]. EGT drops while the proportion of ethanol in the diesel is raised. Due to the fact that ethanol has high evaporative heat and low heating values, it absorbs heat from the engine's combustion region and causes a drop in exhaust temperatures when there is a greater ethanol concentration. The D88E12 fuel combination has recorded the lowest EGT over various load circumstances among all other blends because it contains a higher proportion of ethanol, which reduces ignition delay and releases less thermal energy, consequently reducing the combustion temperature.

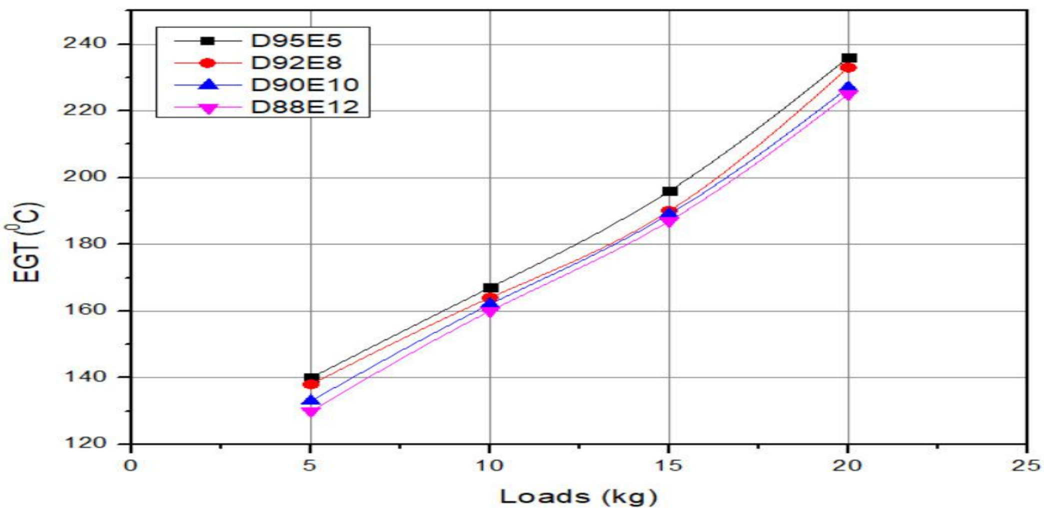

Figure 4: Variation of EGT versus engine loads at 1500 rpm

4.4 TFC

It can be defined as the quantity of fuel used in relation to time. It represents the entire quantity of fuel used by the engine, and it's used for determining power. The TFC assessment offers significant details on engine performance as well as efficiency. This statistic is essential for monitoring energy usage, determining operating expenses, and evaluating the impact on the environment associated with fuel consumption. When the engine's load increases, it must generate more power in order to satisfy demand. In order to produce this additional power, the engine consumes more fuel in the cylinders, which leads to greater fuel consumption. TFC can be calculated by applying the equation down below,

$$TFC = \frac{Z \times w \times 3600}{t \times 1000} \tag{17}$$

Where, Z = Volume of fuel consumed
w = Specific Gravity of fuel
t = Time needed for 10 cc of fuel consumption

Equation (17) explicitly reveals that TFC is influenced by both the fuel density utilised during the test and the time needed to consume 10 cc of fuel. Figure 5 shows fuel blends D95E5 and D90E10, showing that each combination has the lowest amount of TFC at various engine loads. D95E5 has the lowest TFC value under low load, whereas D90E10 possesses the lowest value at high load. The finding is due to the interaction between fuel density and the time necessary to consume a certain volume of fuel.

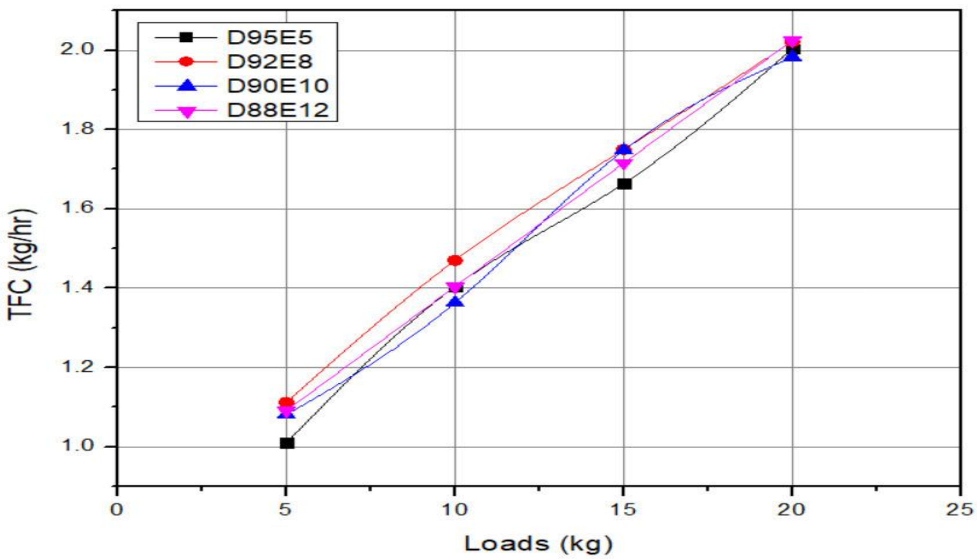

Figure 5: Variation of TFC versus engine loads at 1500 rpm

At higher loads, fuel combinations exhibit greater BTE but lower BSFC. As load increases, correspondingly, BTE, TFC, and EGT increase. Table 14 reveals that the A15 alternative, referred to as D90E10 at 20 kg load, obtained the first rank. In the present experiment, the maximum load was 20 kg, and it is evident that at this load, all fuel mixtures attain maximum BTE; as a result, BSFC declines while EGT and TFC increase as anticipated, suggesting that the engine is performing very effectively. In light of this pattern of behaviour, the 20 kg load was identified as the most optimal load condition among those tested.

Under a 20 kg load, the D95E5 fuel blend produces a slightly higher BTE than the D90E10 blend. At the same load condition, D95E5 exhibits a comparatively lower BSFC than D90E10. Since both BTE and BSFC account for more than 70% of the weight in the assessment, D95E5 emerges as the top-ranked blend based on these two criteria. It is crucial to note that, despite this, the differences between their BTE and BSFC values are extremely close to each other. Furthermore, the D90E10 fuel combination produces exhaust gases at a lower temperature compared to other fuel combinations rated at 20 kg, which implies that it possesses lower thermal loss. Added to that, the engine running with the D90E10 fuel mixture consumes the least amount of fuel among the four-fuel blends used in this study under the same load, leading to more controlled and continuous power generation. After investigating both of these particular criteria, which combined account for more than 20% weight of the total evaluation, and it is apparent that the D90E10 fuel combination outperforms the D95E5 fuel mixture under this load. This dominance creates the ability to deliver the best value by ensuring the engine runs more efficiently. Although D95E5 fuel combination did well in the previous two criteria, it was not far behind D90E10 fuel combination, but D90E10 fuel mixture surpassed in these two criteria by a substantial margin.

After analysing all of the data, it is readily apparent that the D90E10 fuel mixture consistently outperforms the other fuel blends studied in this study, earning it the highest ranking as decided by the hybrid combination FAHP with TOPSIS.

5. Conclusion

In the current study, the impact of adding ethanol in varying proportions by volume to diesel fuel on the operating characteristics of a 4-cylinder compression ignition engine under various loads was examined, and a hybrid combination of the FAHP MCDM technique was used to determine the best optimal alternative based on performance parameters. The research findings are summarised in the following points.

- BTE for all fuel mixtures rises with load, and the D95E5 fuel combination delivers the highest BTE on each load.
- BSFC for all of the fuel combinations declines with load, and the D95E5 fuel combination exhibits the least BSFC value for each load.

- EGT climbed with the rise in load throughout each of the fuel categories.
- EGT drops as the amount of ethanol in the diesel increases.
- The FAHP-TOPSIS technique was applied to assign rankings to four different kinds of fuel combinations (D95E5, D92E8, D90E10, and D88E12) in accordance with experimentally obtained BTE, BSFC, EGT, and TFC engine performance parameters.
- Fuzzy AHP was employed to determine the weights of each criterion, which are then ranked using TOPSIS for fuel.
- Applying the FAHP MCDM strategy, BTE turned out to be the most heavily weighted criterion among all.
- On the basis of the closeness coefficient values derived by the TOPSIS technique, each of the fuel combinations performs more effectively under higher load conditions as compared to low load conditions.
- The FAHP-TOPSIS analysis showed that the D90E10 fuel blend performed most effectively under 20 kg of load and was thus selected as the best option among the others.

This study's decision-making approaches could assist manufacturing firms in analysing and electing the most effective ethanol-diesel fuel combination for their CI engines.

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