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Optimizing CI Engine Ethanol Fuel Induction Techniques using the AHP-PROMETHEE II Hybrid Decision Model.

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Abstract

Ethanol along with nanoparticles stands out as a promising alternative in the pursuit of environmentally sustainable fuel options, offering a potential solution to the dual challenge of curbing NOx and PM/soot emissions while optimizing engine performance in compliance with stringent pollution regulations for compression ignition (CI) engines. The research study aims to optimize ethanol fuel induction techniques for CI engines. It utilizes a hybrid decision-making approach that integrates the analytic hierarchy process-AHP- for problem structuring and the derivation of preference weights. Subsequently, the preference ranking organization method for enrichment evaluations-PROMETHEE II is applied to assess and rank the existing alternatives. The study entails a methodical assessment of diverse ethanol induction methods across varying engine load ranges, considering multiple criteria including engine performance, emissions, combustion behavior, and exhaust after-treatment efficiency. Hybrid AHP-PROMETHEE II model provides criteria weights and ranks ethanol induction techniques and fuel blends across low, medium, and high engine loads for decision-making. It ensures that the method chosen aligns with goals, such as reducing NOx and soot emissions, optimizing engine performance, enhancing combustion, and minimizing exhaust after-treatment costs for CI engines. According to the research findings, the hybrid AHP-PROMETHEE II model identifies the CI engine operating at medium load with ethanol blending (DE10) and without the use of nanoparticles as the preferred choice. Additionally, AHP-PROMETHEE II (AHP derived criteria weights) and PROMETHEE II (direct rating derived criteria weights) models, suggested DE10 with nanoparticle (DE10_NP) using blending technique at low load and combined

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blending-fumigation technique with nanoparticles at high load. However, at medium load, PROMETHEE II recommends DE10_NP, while AHP-PROMETHEE II recommends DE10 blending technique. To assess the performance and reliability of this model, the consistency ratio and Spearman's rank correlation coefficient indices were computed, yielding values of 0.05 and 0.59, respectively. Both indices fall below the predetermined threshold limits, indicating a high level of consistency of the model.

Introduction

Diesel-powered vehicles have been gaining significant market share in the Indian automotive industry, owing to their inherent advantages, including enhanced efficiency and power. However, the simultaneous reduction of NOx (Nitrogen oxides) and PM/soot emissions while maintaining optimal engine performance and adhering to rigorous pollution regulations presents a formidable challenge for the automobile sector.[1] Many researchers have focused towards the utilization of ethanol as an alternative for diesel *fuel.* This is because of ethanol's renewability, biodegradability, and its capacity to reduce greenhouse gas emissions, making it a promising alternative in the pursuit of environmentally sustainable fuel options.[2–4] To utilise ethanol in CI engines, researchers proposed many techniques, including diesel-ethanol blending, diesel-ethanol-additives blending, ethanol-diesel fumigation. The diesel-ethanol blending technique has been found to improve engine efficiency while reducing soot and PM emissions. However, it can lead to increased emissions of NOx, HC, and CO.[5–7] On the other hand, increasing the proportion of diesel-to-ethanol replacement may lead to a more significant simultaneous reduction in PM/soot and NOx in CI engines.[8] However, this enhancement in emissions control might come at the expense of engine performance, as noted in previous studies.[5,6,9] The ethanol fumigation approach has demonstrated a reduction in NOx, soot, and PM emissions, but it has the opposite effect of increasing HC and CO emissions, which is in contrast to the impact of diesel-ethanol blending. Furthermore, this approach has been associated with a greater pressure rise rate and an extended ignition delay period, both of which can lead to decreased engine performance, including reduced brake thermal efficiency and uncontrolled combustion.[10–17] Consequently, to maximize the benefits of both blending and fumigation, researchers have proposed the simultaneous use of ethanol in two fuel induction techniques (combined blending and fumigation).[11] However, it's important to note that the results obtained through this combined approach do not reach the same extent as those observed in either the blending or fumigation technique alone. The incorporation of metal-based nanoparticles into diesel-ethanol or diesel-ethanol-biodiesel blends has shown promising results. This addition increases energy efficiency, combustion efficiency, and heat release rates due to the catalytic action of the nanoparticles. Consequently, this leads to a reduction in NOx, HC, and CO emissions. Moreover, it significantly improves engine performance by reducing ignition delay periods.[4,18–24] Additionally, the incorporation of metal-based nanoparticles into these fuel blends enables the utilization of a higher fraction of ethanol, resulting in a more substantial reduction in PM or soot emissions.[25,26]

Consequently, there is a need for experimental investigations to be conducted to assess the impact of ethanol fuel induction techniques, both with and without the use of metal oxide-based nanoparticles like ZnO. These experiments should focus on evaluating emissions, engine performance, combustion characteristics, and exhaust after-treatment economy under different operating loads and conditions of CI engines.

The diverse outcomes observed in these experiments pose a challenge in identifying the optimal ethanol fuel techniques and fuel blends (diesel-ethanol or diesel-ethanol-nanoparticles) across a range of engine loads, including low, medium, and high. The evaluation of these fuel induction techniques and fuel blends involves a comprehensive assessment across multiple criteria, including performance, combustion characteristics, emissions, and after-treatment economy. Moreover, these evaluations are conducted under different operating conditions, spanning low, medium, and high engine loads. There are studies that utilize the multi-criteria decision-making (MCDM) method to develop comprehensive model to identify the most suitable alternative fuels under different operating conditions. MCDM is a fundamental approach to addressing decision-making challenges, particularly when the goal is to identify the optimal alternative by taking into account multiple criteria in the selection process.[27,28] In the study conducted by Sakthivel *et al*., a hybrid MCDM technique is implemented to optimize the selection of the biodiesel blend (Fish oil) from a set of six alternative fuel blends. The alternatives encompass pure diesel, B20, B40, B60, B80, and B100. This hybrid MCDM approach integrates the analytic network process (ANP) for assigning weights to evaluation criteria through pairwise comparisons. Subsequently, the technique for order of preference by similarity to ideal solution (TOPSIS) is employed to analyze the data and rank the alternative fuel blends.[29] Sinan Erdoğan *et.al.* studied the application of innovative hybrid MCDM techniques, specifically step wise weight assessment ratio analysis (SWARA) - multi-objective optimization on basis of ratio analysis (MULTIMOORA) and ANP - MULTIMOORA, to determine the best fuel for CI engines. Through this analysis, it was concluded that VOB20 (vegetable oil biodiesel with a 20% blend) emerged as the top-performing fuel, while AFB100 (animal fat biodiesel with a 100% blend) ranked as the least favourable option among the nine types of fuels considered. The fuels considered in the study comprised diesel, biodiesel derived from vegetable oil, biodiesel derived from animal fat, and various blends of these fuels.[27] Sinan Erdoğan *et.al.* studied on the application of the MCDM technique model known as operational competitiveness rating analysis (OCRA). This technique is used to assess and evaluate the test results by comparing data related to performance, combustion, and emission criteria between a thermal barriers coated (TBC) diesel engine and an uncoated standard (STD) engine. In the OCRA method, the weights allocated to the criteria can be determined through analytic hierarchy process, SWARA, or a simpler method based on subjective assignment, where experience plays a significant role in determining the weights.[30] M.K. Balki *et al*. employed a hybrid method known as SWARA-ARAS (additive ratio assessment) to determine the optimal operating parameters. These parameters included three distinct factors: ignition timing, compression ratio, and air-fuel ratio. The study entailed experimental investigations conducted across 81 varying conditions. The results of this research facilitated the identification of the most optimal operating parameters for the utilization of methanol fuel, which include a compression ratio of 9:1, an air-fuel ratio of 1.1, and an ignition timing of 20^0 CA.[31]

The literature reveals that MCDM methods are a valuable approach for investigating and optimizing working conditions based on multiple criteria when using alternative fuels in engines. Several studies have employed these methods, often in hybrid combinations, to evaluate results comprehensively. These studies have used various methods, including ANP, AHP, and SWARA, to determine criteria weights. Optimization techniques like TOPSIS, PROMETHEE, and MULTIMOORA have then been applied to make informed decisions. However, the use of hybrid models in MCDM is relatively limited. Specifically, there is a lack of literature regarding the use of a hybrid model combining analytic hierarchy process-AHP and preference ranking organization method for enrichment evaluations-PROMETHEE II for selecting optimal operating conditions or the best alternative fuel blends for internal combustion engines.

The aim of this study is to establish a decision method that assesses various ethanol fuel induction techniques and blends across a range of operating loads. Employing a hybrid approach, this study combining AHP for criteria weighting and PROMETHEE II to rank the alternatives. The practical application of this approach is directed towards the development of ethanol fuel induction control strategies. These strategies are designed to enhance the cleanliness, performance, and cost-effectiveness of compression ignition (CI) engine operation across a spectrum of load conditions, including low, medium, and high engine loads. The study aims to contribute to advancements in CI engine performance by offering insights into the most effective ethanol fuel configurations and induction methods for various operational demands.

Materials and Experimental Methodology

Test Fuels and Experimental Setup

The fuels utilised in this study were commercially available diesel and ethanol (purity> 99.5%). In addition, ZnO- nanoparticles (100 ppm, 20nm) were used as an additive in a diesel-ethanol (DE10) blend to prepare diesel-ethanol-nanoparticle (DE10_NP) blend. The properties of diesel, ethanol, and DE10 were measured and reported in Table 1 using ASTM standards for these investigations. In this study, single-cylinder CI engine was tested using several fuelling techniques, such as blending (DE10), ethanol fumigation (Fumigation), and combined blending-fumigation (DE10 + Fumigation), with and without the use of nanoparticles.

Table 1: Properties of test fuels

Properties	Unit	ASTM standard	Diesel	Ethanol	Diesel ethanol blend (DE10)
Ethanol part	v/v%	--	0	100	10
Density at 15 °C	kg/m3	D287	816	749	805
Lower calorific value	kJ/kg°K	D4809	42856	20850	40570
Higher calorific value	kJ/kg°K	D4809	45310	23304	43024
Flash point	°C	D9358T	53	24	49
Fire point	°C	D9358T	56	31	54
Kinematic viscosity @ 40 °C	cst	D445	2.09	1.29	1.89

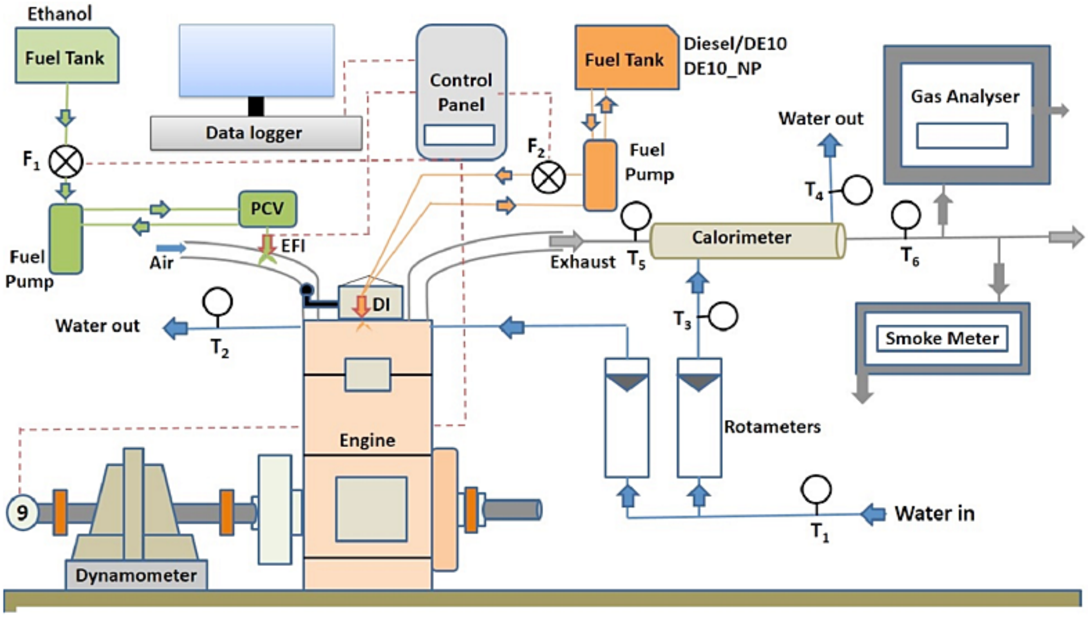
The experimental configuration comprises a single-cylinder, four-stroke CI research engine with an eddy current dynos, for loading. The engine's specifications are presented in Table 2. The research engine included an additional fuel supply system with ethanol injection to the intake manifold for ethanol fumigation. Exhaust gases were also sampled in the tailpipe for HC, CO, NOx, and smoke emission analyses. The HC, CO, and NOx were measured with an AVL DIGAS 444N 5-gas analyzer and the smoke value with an AVL 437 smoke meter. Table 3 lists the specifications of the exhaust gas analyzer and smoke meter. Fig.1 displays a diagram of the CI engine experimental arrangement, the ethanol fumigation system, and exhaust measurements.

Table 2: Engine specifications

Parameters	Specifications
Engine type	Single cylinder 4-stroke research CI engine
Max. power (kW)	3.5
Speed (rpm)	1500
Bore (mm)	87.5
Stroke (mm)	110
Displacement (cc)	661.5
Compression ratio	17.5
Fuel injection timing	0-25°BTDC
Intake system	Natural aspiration

Table 3: Specifications of gas analyzer and smoke meter

Equipment	Parameter measured (Unit)	Resolution
AVLDIGAS444N 5-gas exhaust analyzer 10 (>2000ppm)	Carbon monoxide (CO) (%Vol.) Unburned hydrocarbons (HC) (ppm)	0.001 1 (<2000ppm)
	Carbon dioxide (CO2) (% Vol.)	0.1
	Oxygen (O2) (% Vol.)	0.01
	Nitrogen oxide (NOx) (ppm)	1
AVL437 smoke meter	Opacity (%)	0.1
	Absorption (m-1)	0.01



T_1 - Engine water inlet temperature ; T_2 - Engine water outlet temperature

T_3 - Calorimeter water inlet temperature; T_4 - Calorimeter water outlet temperature

T_5 - Exhaust gas temperature before calorimeter;

T_6 - Exhaust gas temperature after calorimeter;

F_1 -Ethanol fuel measuring unit ; F_2 - Diesel fuel measuring unit

EFI -Ethanol fuel injector; DI- Diesel/DE10/DE10_NP injector; PCV - Pressure control valve

Fig.1: Schematic diagram of CI engine test rig along with ethanol fumigation system

Experimental Procedure for Data collection

Several test runs were conducted on a single cylinder compression ignition engine under various operating conditions. Observations of engine performance, combustion, and emission attributes were conducted at low (0-20%), medium (40-60%), and high (80-110%) engine loads using blending (DE10), ethanol fumigation (Fumigation), and combined blending-fumigation (DE10 + Fumigation) fuel testing techniques with DE10 and DE10_NP fuel blends. After several engine runs at each engine load, the desired quantity of ethanol (10% in blending and 30% in fumigation, combined blending-fumigation) and diesel at each engine load was pre-calibrated by adjusting the diesel pump sleeve and ethanol injection was controlled by the ECU based on input from external sensors and the testing parameters.

MCDM methodology

The objective of this study is to select the optimal ethanol fuel induction technique for various engine loads based on diverse criteria, employing a two-step approach that combines two distinct multi-criteria decision-making methods. The proposed hybrid model, consisting of AHP-PROMETHEE II, operates in two phases: firstly, the AHP method determines the criteria weights, and secondly, the PROMETHEE II method ranks alternatives in descending order of preference. The methodology proposed is elaborated in the subsequent sections.

Selection of Alternatives

In this experiment, the engine was operated across a range of loads, including low load (0-20%), medium load (40-60%), and high engine load (80-110%), using various fuels (diesel, DE10, DE10_NP) and different fuelling techniques (blending, fumigation, and combined blending-fumigation). At each load range, combustion performance, emissions, and after-treatment requirements are expected to vary depending on the choice of fuels and fuelling techniques. Experimental studies comprised a total of 18 distinct alternatives, each coded as per the definitions outlined in Table 4.

Table 4: No. of alternatives and their coding

No.	Alternatives	Description	Coding
1	Low load-Diesel	Single diesel fuel induction at low load	LA1
2	Low load-DE10	Diesel-ethanol blending at low load	LA2
3	Low load-DE10_NP	Diesel-ethanol blending with nanoparticles at low load	LA3
4	Low load-Fumigation	Ethanol fumigation at low load	LA4
5	Low load-DE10+Fumigation	Combined blending-fumigation at low load	LA5
6	Low load-DE10_NP+ Fumigation	Combined blending-fumigation with nanoparticles at low load	LA6
7	Medium load-Diesel	Single diesel fuel induction at medium load	MA1
8	Medium load-DE10	Diesel-ethanol blending at medium load	MA2
9	Medium load-DE10_NP	Diesel-ethanol blending with nanoparticles at medium load	MA3
10	Medium load-Fumigation	Ethanol fumigation at medium load	MA4
11	Medium load -DE10+ Fumigation	Combined blending-fumigation at medium load	MA5
12	Medium load -DE10_NP+ Fumigation	Combined blending-fumigation with nano -particles at medium load	MA6
13	High load-Diesel	Single diesel fuel induction at high load	HA1
14	High load -DE10	Diesel-ethanol blending at high load	HA2
15 1	High load -DE10_NP	Diesel-ethanol blending with nanoparticles at high load	HA3
6	High load -Fumigation	Ethanol fumigation at high load	HA4
17	High load -DE10+Fumigation	Combined blending-fumigation at high load	HA5
18	High load -DE10_NP+ Fumigation	Combined blending-fumigation with nano -particles at high load	HA6

Table 5: Data of the criteria according to alternatives

Altern-atives	Criteria																	
		Combustion (CS1)					Emission (CS2)					Performance (CS3)			Exhaust after-treatment economy (CS4)			
	CP MAX (bar)	**RPR MAX (bar)**	**NHR (J/°θ)**	**CD (°θ)**	**DP (°θ)**	**NOX (PPM)**	**SOOT (%OPA)**	**HC (PPM)**	**CO (%v)**	**CO2 (%v)**	**EGT (°C)**	**BTE (%)**	**BSFC (Kg/kWh)**	**VOLE (%)**	**BP (kW)**	**UC (Kg/h)**	**PFC (Kg/h)**	**REOC**
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
LA1	44.27	2.62	27.10	56.75	8.50	155.33	11.67	9.33	0.06	1.53	145.88	5.81	3.00	77.33	0.38	0.76	0.03	2.80
LA2	44.10	2.73	27.98	57.83	9.33	139.33	7.17	23.00	0.06	1.57	121.16	6.16	2.90	77.31	0.40	0.66	0.09	2.74
LA3	44.07	2.73	27.73	55.33	8.00	155.67	7.97	20.67	0.07	1.80	130.59	5.73	3.07	76.61	0.40	0.75	0.07	3.16
LA4	40.63	1.77	23.65	58.75	9.00	43.33	8.57	81.67	0.13	1.33	133.32	5.62	4.29	77.49	0.40	0.14	0.05	1.63
LA5	40.56	1.63	22.65	58.92	8.67	52.00	7.13	83.67	0.12	1.47	130.67	5.83	4.10	77.65	0.40	0.22	0.99	3.76
LA6	40.49	1.80	23.60	59.42	9.00	67.67	6.57	85.67	0.16	1.73	147.31	5.61	4.25	76.50	0.39	0.37	0.42	3.76
MA1	52.69	4.88	45.90	50.00	7.50	452.00	27.30	12.50	0.06	2.95	212.43	18.87	0.45	76.82	1.76	0.58	0.07	1.90
MA2	52.61	4.65	43.88	51.88	6.75	423.50	17.85	24.50	0.06	2.80	189.56	18.51	0.43	76.66	1.77	0.56	0.12	1.95
MA3	53.01	4.80	45.35	51.38	6.75	562.00	15.45	33.00	0.08	3.90	196.53	19.13	0.44	75.91	1.78	0.75	0.23	2.46
MA4	47.53	2.95	34.93	55.00	8.50	236.00	11.25	320.50	0.14	2.40	176.93	21.43	0.47	77.33	2.45	0.30	0.41	1.90
MA5	44.54	2.28	32.90	57.50	9.00	221.00	15.80	237.50	0.18	3.00	179.36	21.70	0.48	76.42	1.79	0.29	0.70	2.31
MA6	42.91	2.05	33.28	59.13	7.25	249.00	19.50	177.00	0.14	2.70	179.03	20.57	0.53	76.67	1.80	0.34	0.21	2.31
HA1	58.49	5.38	49.80	52.08	5.17	673.67	62.53	28.00	0.20	4.83	319.93	24.23	0.35	75.58	3.30	0.65	0.07	1.67
HA2	59.34	5.38	50.09	49.67	5.00	815.33	31.37	51.00	0.25	5.87	283.55	24.62	0.34	75.82	3.31	0.84	0.13	1.88
HA3	59.40	5.52	51.42	47.00	4.33	763.00	18.13	60.33	0.36	6.03	293.19	23.44	0.36	74.78	3.32	0.77	0.24	2.06
HA4	58.98	5.32	51.85	49.50	4.83	668.33	30.97	134.33	0.18	4.50	269.25	27.85	0.34	75.42	3.68	0.69	0.17	1.72
HA5	59.41	5.58	54.42	47.83	4.33	772.67	25.87	186.00	0.17	5.53	247.20	25.91	0.36	75.68	3.35	0.86	0.18	1.92
HA6	59.26	5.42	54.23	48.00	3.17	737.00	17.10	172.00	0.18	5.20	262.37	28.43	0.35	75.12	3.37	0.80	0.38	1.92

Criteria Identification

This section involves identification of criteria to evaluate 18 alternative for optimization of ethanol fuel induction techniques and fuel blends. This comprehensive assessment considered 18 specific criteria would be taken into account, including maximum cylinder pressure (CPMAX), maximum rate of pressure rise (RPR MAX), net heat release (NHR), combustion duration (CD), delay period (DP), NOx, SOOT, HC, CO, CO2, exhaust temperature (EGT), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC),brake power (BP), volumetric efficiency (VOLE), urea consumption for SCR (UC), post fuel consumption for regeneration (PFC), and relative engine operating cost (REOC). These criteria values against each alternatives were calculated and measured from the engine test results to form initial data value matrix as shown in Table 5. Criteria such as SCR-out NOx, high aqueous urea consumption, fuel or energy requirements for on-board active regeneration of the particle filter, and relative operating expenses of engine after-treatment systems were calculated using Eq. (1-6) to estimate after-treatment economy, with the corresponding data values provided in Table 5.

$\dot{m}_{urea}$=(Engine out Nox-0.4)×($\dot{m}_{diesel}$-$\dot{m}_{ethanol}$ ($CV_{ethanol}$/ CV_{diesel}) ...(1)

$ITHE_{SCR\ CORRECTED}$)=IP/($\dot{m}_{urea}$+$\dot{m}_{diesel}$)×CV_{diesel}+ ($m_{ethanol}$×$CV_{ethanol}$) ...(2)

$\dot{m}_{PFC}$=$\dot{m}e_{g\ Cpeg}$ ($T_{regeneration}$- $T_{exhaust}$)/CV_{PFC} ...(3)

$E_{regeneration}$= m_{eg} C_{peg} ($T_{regeneration}$- $T_{exhaust}$) ...(4)

ITHE $_{PF\ CORRECTED}$ =IP/($\dot{m}_{PFC}$ CV_{PFC}+ $\dot{m}_{diesel}$) $CV_{diesel)}$+ ($\dot{m}_{ethanol}$×$CV_{ethanol}$) ...(5)

$$REOC = \left(\frac{RP}{RP_{max}}(EF) + (1-EF)\right)\left(\frac{ITHE_{Diesel}}{ITHE_{SCR\&PFcorrected}}\right) - 1 \quad ...(6)$$

AHP Decision Model

AHP is a methodical decision technique designed to assist individuals or groups to deal with complex decisions. It accomplishes this by organizing these decisions into a hierarchical structure of clusters, criteria, and alternatives. In this approach, the procedural steps are as follows.[32]

Criteria Identification Decision Structure

AHP model consists of criteria identification decision structure with goal at first level, clusters at second level and criteria at third level.

Pairwise Comparisons

A fundamental aspect of AHP is the pairwise comparison process. For each pair of criteria and sub-criteria, individuals or decision-makers are asked to make judgments about their relative importance using saaty's scale.[32] In this study, the pair wise comparison matrix was formed to determine the significance of criteria in relation to the objective. as per Eq. (7). After generating pair wise comparison matrix of clusters and criteria, each element within matrix is normalised by Eq. (8).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} (a_{ii} = 1, a_{ji} = {}^{1}/_{a_{ij}}, a_{ii} \neq 0, a_{ij} = {}^{w_i}/_{w_j}) \quad ...(7)$$

Where, a_{ij} represent the importance of criterion i over criterion j based on the scale of relative importance.

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad ...(8)$$

$W_i = \frac{1}{n}\sum_{j=1}^{n} a'_{ij}$; W_i represent cluster weightage ...(9)

W_{eci}=W_i×W_{ci} ; W_{ci} represent criteria weightage;

W_{eci} represent effective criteria weightage ...(10)

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{\sum_{j=1}^{n} a_{ij}.W_i}{W_i}\right] \quad ...(11)$$

CI= λmax-n/n-1 ...(12)

CR= CI/RI ...(13)

Computation of Priority Vector

Each row in the normalized matrix, as per Eq. (9-10), undergoes summation, followed by division by the matrix's size and averaging to derive the weights for each criterion. These resultant weights are designated as priority vectors.

Calculation of Consistency Ratio

The consistency ratio (CR) is used to evaluate consistency. To calculate CR, begin by determining the eigenvalue of the matrix (λmax) using Eq. (11), then calculate the Consistency Index (CI) with Eq. (12). To assess consistency, knowledge of the 'random index' (RI) is required, and RI values corresponding to each matrix size can be found as per Satty's data.[32] The consistency ratio is calculated using Eq. (13), and a value below 0.10 indicates a consistent comparison matrix.

Weight Calculation

After collecting the pairwise comparison judgments and passing the consistency check, the calculated weights for each cluster and criterion are employed to compute scores or rankings for each alternative concerning each criterion.

PROMETHEE II Decision Model

This decision model offers a structured framework for decision analysis, facilitating informed choices in scenarios with multiple criteria and diverse decision-maker preferences. It is an extension of the original PROMETHEE method, with PROMETHEE-II being preferred for its ability to provide a complete ranking of alternatives.

The processing steps for PROMETHEE II techniques are follows,[33,34]

$$D= \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & . & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad ...(14)$$

Where,
A_1, A_2……Am= numbers of alternatives
X_{11}, X_{12}…..X_1n=values of n number of criteria for alternatives.

The evaluation criteria data are categorized into beneficial and non-beneficial criteria to prioritize the alternatives

Create normalize evaluation matrix according the nature of the selected criteria using Eq. (15) for non-beneficial and Eq. (16) for beneficial criteria.

$$R_{ij} = \frac{[\max(Xij) - Xij]}{[\max(Xij) - \min(Xij)]} \quad ...(15)$$

$$R_{ij} = \frac{[Xij - \min\,(Xij)]}{[\max(Xij) - \min(Xij)]} \quad ...(16)$$

The evaluative differences (deviations) are calculated using Eq. (17) by assessing the variances of the ith alternative compared to the other alternatives.

$$D\ (M_a - M_b) = R_{(ij)a} - R_{(ij)b} \quad ...(17)$$

Evaluating the preference function (Pj) involves using the conditions outlined in Eq. (18-19). If the difference (D) between Ma and Mb is less than or equal to zero, the preference function value is set to zero. Conversely, when D (Ma - Mb) is greater than zero, the preference function value is determined using the differences (R (ij) a − R (ij) b).

Take $P_j(M_a, M_b) = 0$, If $R_{(ij)a} \leq R_{(ij)b}$, then $D\ (M_a - M_b)\ ) = 0$ ...(18)

Take $P_j(M_a, M_b) = R_{(ij)a} - R_{(ij)b}$, If $R_{(ij)a} > R_{(ij)b}$, then $D\ (M_a - M_b) > 0$ ...(19)

Calculating the aggregate preference function, π (Ma, Mb), as per Eq. (20). For this calculation, both direct rating-derived criteria weights and AHP-derived criteria weights were taken into account. This inclusion of direct rating-derived criteria weights is a part of the sensitivity analysis for the proposed hybrid model. This process entails comparing the outcomes of the hybrid AHP-PROMETHEE-II approach with those of the PROMETHEE II decision model, providing insights into the influence of criteria weighting methods on ranking preferences.

$$\pi\ (M_{a,}\ M_b) = \frac{\sum_{j=1}^{n} WjPj(Ma,Mb)}{\sum_{j=1}^{n} Wj} \quad ...(20)$$

Calculate the surplus and deficit outranking flow of the alternatives using Eq. (21-22) for both PROMETHEE II and AHP-PROMETHEE-II models. The net outranking flow for the alternatives is computed solely for PROMETHEE II and AHP-PROMETHEE II models, enabling the comprehensive ranking of the alternatives. Additionally, calculate the net flow for all options as per Eq. (23). Subsequently, rank the alternatives in descending order based on the net flow (φ), thus identifying the best ethanol fuel induction technique for each load range in this study.

Positive flow for alternative, φ+

$$\varphi^{+} = \frac{1}{n-1} \sum_{b=1}^{m} \pi(a,b) \qquad ...(21)$$

Negative flow for alternative, φ-

$$\varphi^{-} = \frac{1}{n-1} \sum_{b=1}^{m} \pi(a,b) \qquad ...(22)$$

Net Flow {φ (a)} = Positive flow {φ+ (a)} –Negative Flow {φ^{-}(a)} ...(23)

To ensure the reliability of comparisons among clusters and criteria in the proposed AHP-PROMETHEE II hybrid model, a consistency ratio (CR) was calculated, demonstrating that the pairwise comparison matrices generated for these clusters and criteria exhibit a high level of consistency by falling below the established threshold of 0.10. This emphasizes the resilience of the model's comparisons. To assess disparity in ranking between two decision models, namely a single PROMETHEE II model and the hybrid AHP-PROMETHEE II model, Spearman's rank coefficient was computed. Resulting value, falling within -1 to +1, indicates a substantial degree of association between rankings generated by these models. Additionally, the results obtained from the proposed AHP-PROMETHEE II model were cross-validated by comparing them with experimental findings reported in the existing literature.

Results and Discussion

The research aims to optimize ethanol fuel induction techniques for CI engines across varying engine load ranges, utilizing a combination of diesel-ethanol (DE10) and diesel-ethanol-nanoparticle (DE10_NP) blends, through the hybrid AHP-PROMETHEE II approach. This approach evaluating a total of 18 alternatives, including various combinations of fuel blends (DE10, DE10_NP), ethanol induction methods (blending, fumigation, and combined blending-fumigation), and engine load ranges categorized as low (0 to 20%), medium (40 to 60%), and high (80 to 110%). In this evaluation process, a comprehensive set of criteria-clusters that includes performance, combustion characteristics, emissions, and after-treatment economy were considered. Within each of these cluster, specific sub-criteria were identified, and their corresponding values are derived from the test results. In the following sections, computation and results of our AHP analysis and the application of PROMETHEE II for prioritizing the alternatives were presented.

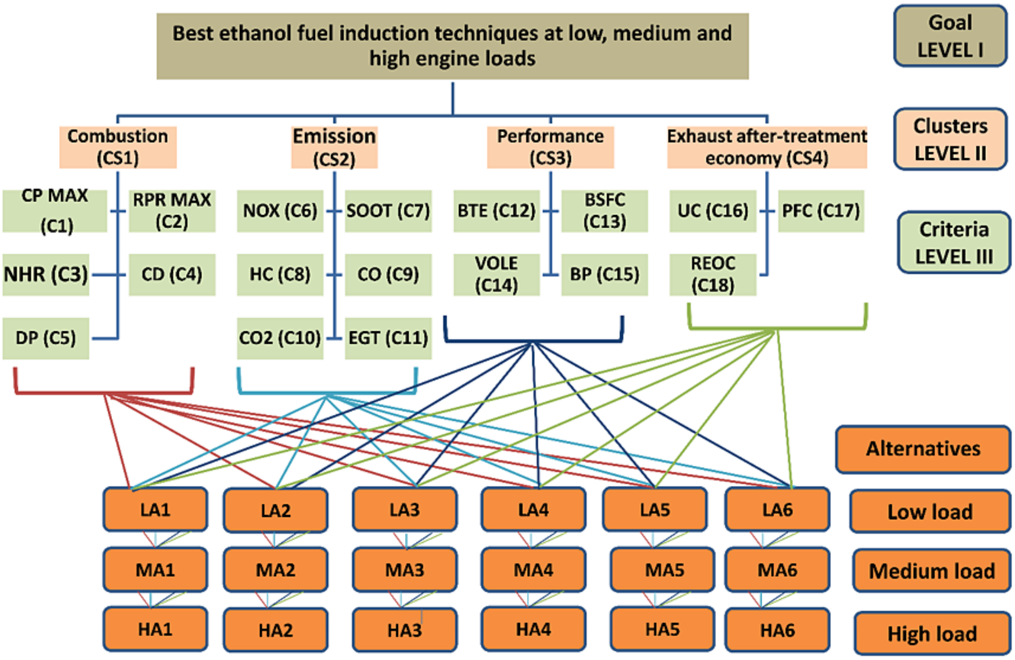


Fig. 2: Criteria identification decision structuring for AHP model

Computation of AHP Model and Results

In this section, analytic hierarchy process –AHP is employed to establish criteria weightage essential for achieving goal of selection of best ethanol induction techniques at each load range. Fig. (2) illustrates the decision structuring process, organizing the criteria into four clusters with a total of eighteen criteria for our AHP model.

In accordance with Saaty's scale,[32] 16 pair-wise comparison of clusters and 86 pair wise comparisons of criteria was formed to establish the significance of clusters and criteria concerning goal. Once generated, these matrices were used to derive normalized matrices for both clusters (Table 6) and criteria (Table 7). Subsequently, computed priority vectors, which provide importance weights for each cluster and criterion. Thus, AHP derived cluster and criteria weight matrix was obtained, as shown in Table 8. For each cluster, a consistency ratio (CR) of 0.05 has been determined, which falls below the established threshold of 0.10. This signifies that the pairwise comparison matrices generated for these clusters exhibit a high level of consistency. Consequently, the calculated weights from the AHP model could be utilised to compute scores and rankings for each alternative concerning each criterion.

Table 6: Normalized clusters matrix

Clusters	Combustion (CS1)	Emission (CS2)	Performance (CS3)	Exhaust after-treatment economy (CS4)
Combustion (CS1)	0.1071	0.1216	0.0735	0.1667
Emission (CS2)	0.5357	0.6081	0.6618	0.5000
Performance (CS3)	0.3214	0.2027	0.2206	0.2778
Exhaust after-treatment economy (CS4)	0.0357	0.0676	0.0441	0.0556

Table 7: Normalized matrix of criteria

CS1	C1	C2	C3	C4	C5	--	CS3	C12	C13	C14	C15
C1	0.0698	0.1500	0.0388	0.0898	0.0664	--	C12	0.5966	0.6908	0.4565	0.4412
C2	0.0233	0.0500	0.0291	0.0719	0.0569	--	C13	0.1989	0.2303	0.4565	0.4412
C3	0.2093	0.2000	0.1165	0.1198	0.0797	--	C14	0.0852	0.0329	0.0652	0.0294
C4	0.2791	0.2500	0.2330	0.3593	0.3985	--	C15	0.1193	0.0461	0.0217	0.0882
C5	0.4186	0.3500	0.5825	0.3593	0.3985	--	--	--	--	--	--
CS2	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**CS4**	**C16**	**C17**	**C18**	**--**
C6	0.4976	0.6122	0.3673	0.3673	0.2917	0.5042	C16	0.2308	0.4286	0.2174	--
C7	0.1659	0.2041	0.3061	0.3061	0.2500	0.3025	C17	0.0769	0.1429	0.1304	--
C8	0.0829	0.0408	0.0612	0.0612	0.1250	0.0336	C18	0.6923	0.4286	0.6522	--
C9	0.0829	0.0408	0.0612	0.0612	0.1250	0.0336	--	--	--	--	--
C10	0.0711	0.0340	0.0204	0.0204	0.0417	0.0252	--	--	--	--	--
C11	0.0995	0.0680	0.1837	0.1837	0.1667	0.1008	--	--	--	--	--

Table 8: AHP derived cluster and criteria weightage

Clusters	CS1	CS2	CS3	CS4	--	--
Weightage	0.12	0.58	0.26	0.05	--	--
Combustion criteria	C1	C2	C3	C4	C5	--
Weightage	0.01	0.01	0.02	0.04	0.05	--
Emission criteria	C6	C7	C8	C9	C10	C11
Weightage	0.25	0.15	0.04	0.04	0.02	0.08
Performance criteria	C12	C13	C14	C15	--	--
Weightage	0.14	0.08	0.01	0.02	--	--
Exhaust after-treatment economy criteria	C16	C17	C18	C16	--	--
Weightage	0.01	0.01	0.03	0.01	--	--

Computation of PROMETHEE- II and Results

In this section, the PROMETHEE II is used to compute the net outranking flows and to create a unified decision model for ranking alternatives. The data values for the evaluation criteria of ethanol fuel induction techniques were obtained at various engine load ranges have been categorized into beneficial and non-beneficial criteria, as illustrated in Table 9.

Table 9: Beneficial and non beneficial criteria

<table>
<tr><th colspan="11">Non beneficial criteria (least values desired)</th></tr>
<tr><th>CD (°θ)</th><th>DP (°θ)</th><th>NOX (PPM)</th><th>SOOT (%OPA)</th><th>HC (PPM)</th><th>CO (%v)</th><th>CO2 (%v)</th><th>BSFC (Kg/kWh)</th><th>UC (Kg/h)</th><th>PFC (Kg/h)</th><th>REOC</th></tr>
<tr><td>C4</td><td>C5</td><td>C6</td><td>C7</td><td>C8</td><td>C9</td><td>C10</td><td>C13</td><td>C16</td><td>C17</td><td>C18</td></tr>
<tr><th colspan="11">Beneficial criteria (maximum values desired)</th></tr>
<tr><th>CP MAX (bar)</th><th>RPR MAX (bar)</th><th>NHR (J/°θ)</th><th>EGT (°C)</th><th>BTE (%)</th><th>BSFC (Kg/kWh)</th><th>BP (kW)</th><th>--</th><th>--</th><th>--</th><th>--</th></tr>
<tr><td>C1</td><td>C2</td><td>C3</td><td>C11</td><td>C12</td><td>C14</td><td>C15</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
</table>

Further these data values given were normalized as per the nature of the criteria using Eq. (15-16). Subsequently, preference function was derived using the conditions outlined in Eq. (18-19). The values of the preference function matrix were then multiplied with both the direct rating-derived weights (Table 10) and AHP-derived weights (Table 8) to calculate an aggregated preference function matrix. The calculated aggregated preference function matrices for both decision models, PROMETHEE II and the hybrid AHP-PROMETHEE II, are used to calculate the surplus, deficit, and net flows for all alternates in both the PROMETHEE II and AHP-PROMETHEE II models were calculated using Eqs. (21-23). the resulting outranking flows are displayed in Table 11. To determine the ranking of alternatives in this study, the decreasing values of the net outranking flow (φ) was considered. This ranking allows to identify the best ethanol fuel induction technique for each load range.

Table 10: Direct rating derived cluster and criteria weightage

Clusters	CS1	CS2	CS3	CS4	--	--
Weightage	0.20	0.45	0.20	0.15	--	--
Combustion criteria	C1	C2	C3	C4	C5	--
Weightage	0.04	0.04	0.04	0.04	0.04	--
Emission criteria	C6	C7	C8	C9	C10	C11
Weightage	0.075	0.075	0.075	0.075	0.075	0.075
Performance criteria	C12	C13	C14	C15	--	--
Weightage	0.05	0.05	0.05	0.05	--	--
Exhaust after-treatment economy criteria	C16	C17	C18	C16	--	--
Weightage	0.05	0.05	0.05	0.05	--	--

Table 11: Outranking flow for PROMETHEE II and hybrid AHP-PROMETHEE II model

Alternatives	Outranking flow for PROMETHEE II model			Outranking flow for hybrid AHP-PROMETHEE II model		
	φ+	φ-	φ	φ+	φ-	φ
LA1	0.1524	0.1752	-0.0227	0.2048	0.1258	0.0789
LA2	0.1438	0.1836	-0.0398	0.1972	0.1294	0.0678
LA3	0.1507	0.1737	-0.0230	0.1995	0.1274	0.0721
LA4	0.0912	0.2960	-0.2048	0.1183	0.2423	-0.1240
LA5	0.2027	0.2450	-0.0423	0.1899	0.2059	-0.0160
LA6	0.1414	0.2466	-0.1052	0.1552	0.2160	-0.0608
MA1	0.1743	0.0995	0.0748	0.2120	0.0816	0.1305
MA2	0.1674	0.0967	0.0707	0.2102	0.0766	0.1336
MA3	0.1771	0.0941	0.0830	0.1992	0.0878	0.1115
MA4	0.1347	0.1653	-0.0306	0.1230	0.1739	-0.0508
MA5	0.1306	0.1819	-0.0513	0.0940	0.2076	-0.1136
MA6	0.1082	0.1729	-0.0647	0.1005	0.1874	-0.0869
HA1	0.1834	0.1584	0.0250	0.1681	0.1872	-0.0190
HA2	0.1949	0.1480	0.0470	0.1685	0.2217	-0.0532
HA3	0.2083	0.1740	0.0343	0.1714	0.3028	-0.1314
HA4	0.1911	0.1267	0.0644	0.1706	0.1493	0.0213
HA5	0.2094	0.1295	0.0799	0.1805	0.1644	0.0161
HA6	0.2274	0.1220	0.1054	0.1804	0.1565	0.0240

Fig. 3 represent the rankings obtained for all 18 alternatives using the hybrid AHP-PROMETHEE II model with AHP-derived weights and the PROMETHEE II model with direct rating-derived weights.

According to the results, the hybrid AHP-PROMETHEE II model ranks the CI engine operated at medium load with ethanol blending, fuelled with (DE10) without the use of nanoparticles as the top choice. Meanwhile, as per the PROMETHEE II model, the engine operated at high load with a combined blending-fumigation approach fuelled with DE10_NP, demonstrates optimal reductions in emissions, performance and combustion enhancements, along with the lowest after-treatment requirements and costs. Additionally, Fig. 4 provides a comprehensive visual representation of the rankings for ethanol fuel induction techniques, categorized separately for low, medium, and high load ranges.

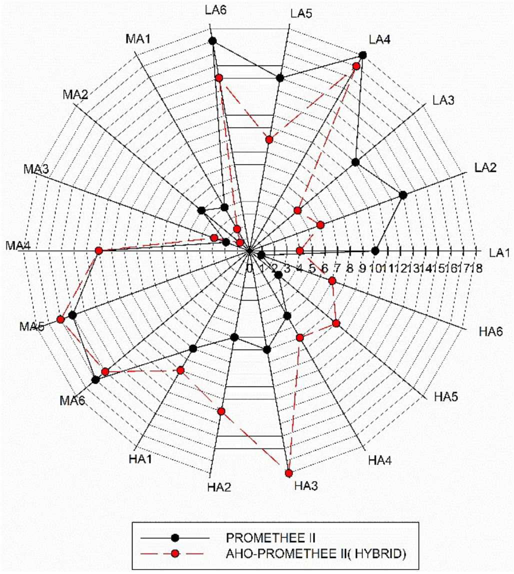


Fig. 3: Priority orders comparison according to PROMETHEE II and hybrid AHP-PROMETHEE II model for all alternatives

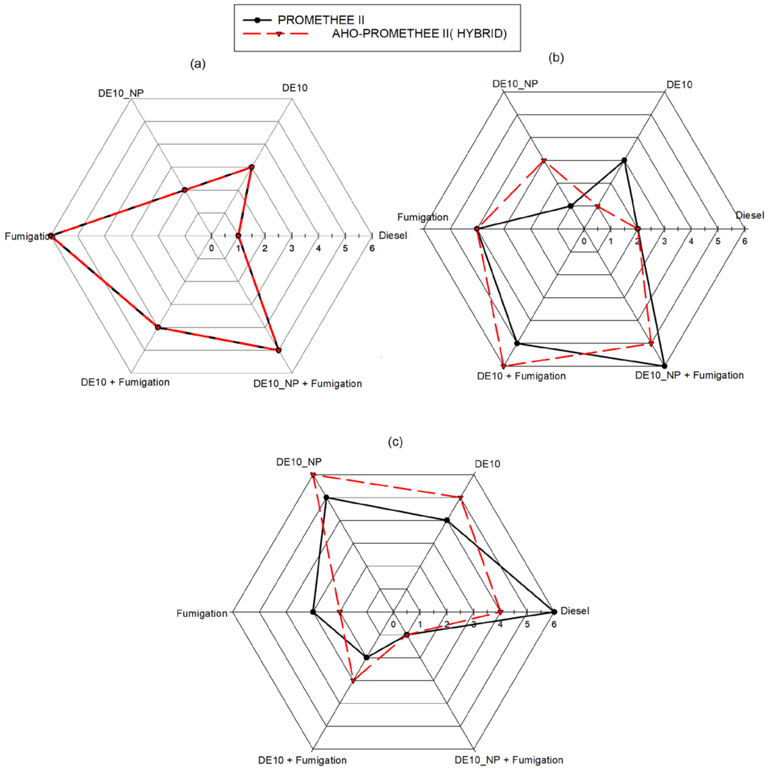


Fig.4: Priority orders comparison according to PROMETHEE II and hybrid AHP-PROMETHEE II model (a) low lad range (b) medium load range and (c) high load range

Results shows specific recommendations for each load range according to the two models. The results indicate that for low load ranges, the optimum ethanol fuel induction technique is blending fuelled with DE10_NP, as determined by both the hybrid AHP-PROMETHEE II and PROMETHEE II models. In the case of medium load ranges, the choice differs slightly between the models. The PROMETHEE II model favours blending fuelled with DE10_NP with nanoparticles, while the hybrid AHP-PROMETHEE II model recommends blending fuelled with DE10. For high load ranges, both models converge on the same choice, identifying the combined blending-fumigation technique with fuel DE10_NP as the optimum ethanol fuel induction technique. Furthermore, for both models, no deviations in preference orders were observed within the low load range. The largest deviation in preference orders was found in the case of high engine load, while for medium engine load, it was intermediate.

Table 12: Comparison of ranks obtained by PROMETHEE II and hybrid AHP-PROMETHEE II and their absolute deviation

Alternatives	PROMETHEE II model	Hybrid AHP-PROMETHEE II model	Absolute Deviation	Square
	Rank	Rank	($\|d_i\|$)	(d_i^2)
LA1	10	4	-6	36
LA2	13	6	-7	49
LA3	11	5	-6	36
LA4	18	17	-1	1
LA5	14	9	-5	25
LA6	17	14	-3	9
MA1	4	2	-2	4
MA2	5	1	-4	16
MA3	2	3	1	1
MA4	12	12	0	0
MA5	15	16	1	1
MA6	16	15	-1	1
HA1	9	11	2	4
HA2	7	13	6	36
HA3	8	18	10	100
HA4	6	8	2	4
HA5	3	9	6	36
HA6	1	7	6	36

The results of these models were contrasted with findings from literature involving engine tests incorporating nanoparticles. Findings from these model indicate that optimal results were achieved when nanoparticles were used in conjunction with ethanol blending techniques at low and medium loading condition. However, for high loading condition the most favorable outcomes were obtained with a combination of blending and fumigation. The literature also revealed the same, which indicate that the use of metal-based nano additives in the diesel-ethanol blending emerges as the preferred technique for reducing HC, CO, and NOx emissions. Additionally, this approach showed improvements in engine efficiency, reduced fuel consumption, and enhanced combustion characteristics. Specifically, improvements were observed in terms of heat release rate, delay period, and combustion duration across all engine load conditions.[4,18–24] Furthermore, it was noted in the literature that nanoparticles exhibit catalytic activity in oxidation reactions. When combined with the presence of ethanol in diesel fuel, this catalytic action led to a reduction in particulate matter (PM) and soot emissions. The utilization of metal-based nanoparticles was found to enhance soot oxidation, subsequently decreasing the need for diesel particulate filter (DPF) after-treatment and regeneration processes.[25,26] Additionally, the combined blending-fumigation technique involving ethanol exhibited superior enhancements in engine performance and combustion parameters. Simultaneously, it resulted in a more substantial reduction in emissions when compared to the use of a simple diesel-ethanol blending approach, particularly at high engine loads.[11] The results obtained using the proposed AHP-PROMETHEE II model align closely with the experimental findings reported in the existing literature. This similarity validating the utility and reliability of the proposed model.

Spearman’s Rank Correlation Coefficient (ρ)

Spearman’s rank coefficient 'ρ' serves as the index for quantifying the non-parametric monotonic relationship between two sets of variables, using Eq. (24). In the context of this study, it is employed to assess the effectiveness of the hybrid AHP-PROMETHEE II model by calculating the deviation in rankings compared to the single PROMETHEE II model. The value of ‘ρ' should lies between -1 to +1. Table 12 presents a comparison of the rankings generated by PROMETHEE II and the hybrid AHP-PROMETHEE II models, along with their corresponding absolute deviations.

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \qquad \text{...(24)}$$

Where,

d_i= pairwise difference between the ranks given by two optimization method.

n = number of variables in associated with the problem.

It provides insight into the degree of agreement or disparity between the rankings produced by the two decision models. The results indicate that the coefficient (ρ) between the two models is 0.59 when considering all alternatives.

Conclusion

In this study, a single-cylinder CI engine underwent testing using different fuel blends, including diesel-ethanol (DE10) and diesel-ethanol-nanoparticle (DE10_NP). Various ethanol fuelling techniques were employed, such as blending, ethanol fumigation, and a combination of blending-fumigation. These tests were conducted over a range of engine loads, including low, medium, and high settings. In total, these experimental studies comprised 18 distinct alternatives, which were evaluated using multi criteria decision making hybrid model to identify optimum ethanol fuel induction techniques and fuel blend at each operating load range. The results obtained in the study were given below.

- To identify the best ethanol fuel induction technique and fuel blend for each engine load condition, a hybrid decision model was introduced, combining Analytic Hierarchy Process (AHP) with PROMETHEE II. In this model, 18 different alternatives were categorized into four clusters: combustion, emission, performance, and exhaust after-treatment economy. A total of 18 distinct criteria were taken into account for the evaluation. These data were collected from engine test runs that covered three different loading conditions and incorporated six various fuelling techniques and fuel blend combinations.
- In hybrid model, AHP model was utilised to compute weights for all four clusters and 18 individual criteria. To accomplish this, a total of 16 pairwise comparisons were conducted for the clusters, and 86 pairwise comparisons were performed for the criteria to establish criteria weights.
- AHP incorporates a consistency check through the consistency ratio (CR). For each cluster, a consistency ratio (CR) of 0.05 has been calculated, which is lower than the predefined threshold of 0.10. As a result, the weights obtained from the AHP model can be confidently used to calculate scores and rankings for each alternative with respect to every criterion.
- The net flow values for all alternates in both the PROMETHEE II (based on direct rating

derived weights) and AHP-PROMETHEE II models (based on AHP-derived weights) were calculated to determine the ranking of alternatives.

- The hybrid AHP-PROMETHEE II model identifies the CI engine operating at medium load with ethanol blending (DE10) and without nanoparticles as the preferred choice. On the other hand, according to the PROMETHEE II model alone, the engine operating at high load with a combined blending-fumigation approach using DE10_NP fuel, demonstrates optimal reductions in emissions, performance and combustion enhancements, along with the lowest after-treatment requirements and costs.
- The results of the two models offer specific recommendations for each load range. At low load ranges, both the hybrid AHP-PROMETHEE II and PROMETHEE II models suggest that the optimal ethanol fuel induction technique is blending with DE10_NP. In the case of medium load ranges, PROMETHEE II model recommends blending with DE10_NP with nanoparticles, whereas the hybrid AHP-PROMETHEE II model recommends blending with DE10. However, for high load ranges, both models reach a consensus, pointing to the combined blending-fumigation technique with DE10_NP as the most suitable ethanol fuel induction technique.
- The results indicate that when considering all available alternatives, the spearman's rank coefficient for both models is 0.59. This suggests a significant degree of correlation between the rankings produced by the two models across different engine load conditions.

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Conflict of Interest

The authors declares no conflict of interest.

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