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A Novel Paradigm CNG Dual-Fuel Strategy to Reduce Engine Emission of a CRDI Engine: A Green Fuel and Multi-Objective Optimization Approach

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ABSTRACT

This study aimed to reduce emissions—specifically smoke, carbon monoxide, nitrogen oxides, and unburnt hydrocarbon alongside brake specific fuel consumption (BSFC) in a dual-fuel mode using Mahua oil blended with compressed natural gas, methanol, and ethanol. BSFC, a key measure of engine fuel efficiency, and the emissions were evaluated with load, injection timing, injection duration, and fuel strategy as input parameters. To minimize trials, Taguchi's L9 orthogonal array was used, with Grey Relational Analysis optimizing the process. The study identified load as the most influential factor. Results showed significant reductions in smoke, CO, NOx, and UHC emissions, while BSFC improved measurably. The study concluded that using this optimization approach effectively enhances engine performance and reduces environmental impact in dual-fuel systems.

INTRODUCTION

For a variety of operating conditions, the diesel engine is extremely flexible and also has an excellent reputation for its high stability, high energy efficiency, and low setup cost. Due to a wide range of applications of fossil fuels which are non-renewable in nature, the energy demand is increasing rapidly throughout the world depending on the economic growth. In the near future, because of the current consumption rate, fossil fuels will be exhausted very soon (Yoon & Lee, 2011, You et al., 2020). Therefore, environmentally friendly fuels are preferred while transitioning to a sustainable reasonable alternative fuel. Because of the low emission of carbon monoxide, optimum fuel usage, low unburnt hydrocarbon (UHC) creation, and high thermal efficiency, the role of compression ignition (CI) engine is very eminent in the

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power generation and modern transportation sector. But most importantly, particulate matter (PM) emissions and nitrogen oxide (NOx) content greatly affect our precious environment produced by these engines (Yoon & Lee, 2011). But how far these diesel engines can be used in the future is a serious question because the petroleum reserves will not last for a long time with the strict rules for petroleum usage used all over the world. So, it is high time that an alternative fuel that performs better in terms of emission than the conventional fuel is ascertained as soon as possible in the current scenario. At low load conditions, the increase in the emission of hydrocarbons and carbon monoxide and a decrease in combustion performance is a major obstacle in diesel dual fuel (DDF) engines (Kohse, 2020, Yuvenda et al., 2020). Because of the trade-off relationship in diesel engines, it is challenging to reduce the PM emission of NOx concurrently. This knowledge can be used to develop various advanced combustion modes to bring down these emissions (Duan et al., 2021, Singh et al., 2020). One of the most promising approaches to be applied to diesel engines which results in proper distribution of mixture, and optimum utilization of fuel (diesel) is the dual-fuel combustion mode which has a great potential to reduce the amount of PM and NOx formation (Hotta et al., 2020, Zhang et al., 2019). Because of the high octane number, compressed natural gas (CNG) is more apt for spark ignition engines (Machado et al., 2020).

However, it is not practicable to initiate the combustion by compression alone, due to its self-ignition temperature of about 5400° and low cetane number. Thus, for initiating the combustion of CNG, there is a requirement for an ignition source which is either a spark from a spark plug in spark ignitation (SI) engine or pilot fuel with high cetane in a diesel engine. CNG can be operated in a diesel engine in dual fuel mode only, since some amount of diesel is required as pilot fuel for initial combustion or ignition of CNG. Diesel fuel is ignited due to the high compression of the diesel engine initially, which then acts as the ignition source for the combustion of premixed CNG with air. The dual fuel mode of operation thus involves two stages of combustion, initially combustion of high cetane fuel (diesel or biodiesel) followed by combustion of high octane CNG. Diesel as a pilot fuel in various proportions, has been used over the years in combination with CNG in dual fuel mode and has been researched extensively in CI engines. The CNG buses emitted more fine particulates but a lesser number of overall particulate matter compared to diesel operation according to Hallquist et al. (2013). According to Karabektas et al. (2014) and Serrano & Bertrand (2013), except for high loads the dual fuel method results in high hydrocarbon and carbon monoxide emissions and low NO emission at all other loads. The increase of pilot fuel quantity was observed to increase with pm emission increase while PM and NOx particulate matter emission is reduced by CNG and energy diesel dual fuel operation as researched by Liu et al. (2013). Yang et al. (2015) conducted an investigation under low load for the diesel pilot and CNG injection parameters on output values using a dual-fuel engine. A common-rail type engine (dual fuel) was taken for the investigation which used a turbocharger. To obtain the optimal parameters the pilot injection timing, pressure, and CNG injection timing were varied. They found out that the exhaust gas (hydrocarbon and carbon monoxide) and the combustion process can be improved with the improvement in diesel pilot pressure, injection advanced timing, and CNG injection timing. At low loads, exhaust gas and combustion performance of DDF engines are both affected by injecting diesel and CNG parameters. Nonetheless, the amount of air entering the cylinder gets reduced in the presence of CNG which in turn reduces the volumetric efficiency (Vadlamudi et al., 2023, Tomita et al., 2002, Selim et al., 2003, Tarabet et al., 2014). This results in reduced oxygen content inside the cylinder as compared to the oxygen content due to a solo fuel (Kalsi et al., 2016), and causes hindrance in chemical activity between air and diesel inside a standard engine. In research by Vadlamudi et al. (2023), a strong negative impact was observed on brake thermal efficiency and indicated mean effective pressure (IMEP) in fuels with a cetane number of more than 45, when he studied the effect of cetane number in dual fuel mode of the pilot fuel. Selim et al. (2003) and Tomita et al. (2002), both came to the same conclusion that to increase the efficiency and reduce the emission (NOx), the usage of moderate exhaust gas recirculation (EGR) was indeed very effective. Paul et al. (2014) found that emission and combustion improvement is limited due to ethanol's property of poor miscibility in diesel when ethanol was used as an additive in the pilot fuel. N-butanol is more suitable as an additive in the pilot fuel because it possesses a high cetane number as compared to ethanol even if its blend with diesel at any ratio is possible.

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Geo et al. (2008) observed improvement in brake thermal efficiency (BTE) and emission of smoke when they used a dual fuel strategy by blending hydrogen with rubber seed methyl ester. Banapurmath and Tewari et al. (2009) observed that BTE and NOx decrease while others like CO and UHC emissions increase after mixing methyl ester and produced gas in dual-fuel operation. Korakianitis et al. (2011), after experimenting using rapeseed methyl ester and gaseous fuel in dual fuel operation found that, hydrocarbon emission increases with natural gas usage while NOx emission increases with hydrogen usage.

Yoon and Lee (2011) studied the dual-fuel combustion characteristics by thoroughly examining the combustion and exhaust emission characteristics. The fuel combinations of the 2.2 ± 0.1 kg/h of biogas with biodiesel as pilot fuel in dual fuel mode exhibited better performance and emitted less amount of soot. The high amount of CNG injection into the engine has not yet been studied properly as compared to the low concentration of CNG in dual-fuel operation in a conventional fuel- CNG engine. Thus, most of the work in the literature is focused on low CNG injection. However, in the current study, an experimental study is presented that gives a comparative result between methanol, mahua methyl ester (MME), and pilot fuel (ethanol) for dual-fuel operation. To obtain the optimal response, CNG and common rail direct injection (CRDI) dual fuel systems given by the conventional diesel platform need to be attuned properly to increase the parametric viability.

The experimental cost and time associated with implementing the orthogonal array approach present a feasibility risk. While this methodology is ideal for exploring the entire design space by varying input variables one at a time, these constraints must be carefully considered. So, to conduct a proper exploration of the design space a methodology is needed which adapts to the above requirement. So, for this Taguchi method establishes an effective approach and a tool that is derived from the design of experimentation theory (Reddy et al., 2020, Panda et al., 2017). But again, the suitability of Taguchi's method to solve multi-objective problems of optimization is often questioned even if the method is very popular for solving optimization problems which is a serious drawback of Taguchi's method. Thus, along with Taguchi's method, Grey relation analysis theory is used in conjunction with it for solving multi-objective optimization problems in a variety of engineering domains including the IC engine paradigm as well (Rai and Sahoo, 2020, Gul et al., 2020). The principal objective behind this study is the concurrent reduction of UHC emission, NOx, co, smoke, and BSFC while zeroing on optimal load combinations, CNG energy share (CES), blends of different fuels, and fuel injection timing (BTDC).

PILOT FUELS AND THEIR PROPERTIES

The primary fuel pit to use in this experiment is ethanol and methanol as an additive and MME i.e., Mahua oil methyl ester (high-speed). MME is a unique fuel that is a combination of saturated fatty acids and mono-alkyl ester of different chain lengths and is biodegradable along with being renewable and nontoxic (Raman and Kumar, 2020). The transesterification process also known as alcoholysis is a special type of reaction in which the alkyl group is substituted in place of esters to change the original ester. In this reaction, by combining the reactants, the conversion takes place. However, even if being an equilibrium reaction, catalysts can be used to control and adjust the equilibrium. Equation (1) represents transesterification and molecular structure. As an oxygen-rich material, ethanol is added to blended fuel to boost oxygen content. Studies by Panda et al. (2018) suggested that the addition of a small percentage of oxygen-rich fuel can reduce the emissions level drastically. Methanol is added to raise cetane number (Singh et al., 2020) and lower the ignition point. Locally supplied CNG is the major fuel. Fig 1 summarizes the fuel properties.

$$\text{RCOOR'} + \text{R''OH} \leftrightarrow \text{RCOOR''} + \text{R'OH} \tag{1}$$

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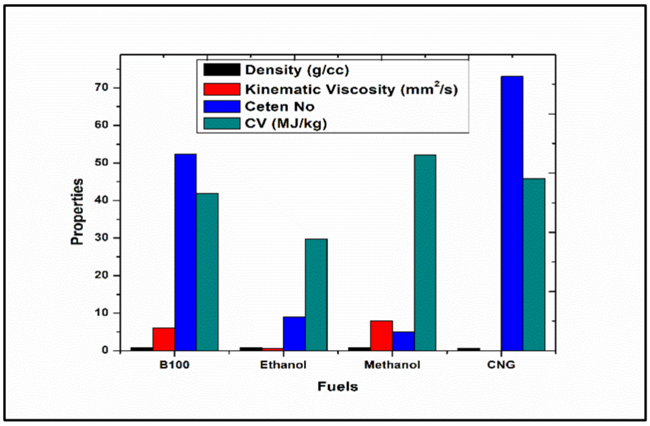

Fig. 1. Fuel properties.

APPARATUS DESCRIPTION

Fig 2 illustrates the experimental setup which comprised of an engine having single cylinder 4 strokes joined with a hay CRDI fuel injection system. Table 1 gives all the details of this setup. An Eddy current air-cooled dynamometer (make) was coupled with the IC engine. In the setup, the CRDI acts as an attachment to the engine which contains a fuel pump and injector of very high pressure, rail, and electronic injection system which is the heart of the system. All these are described in Table 2 as the fuel injection system. At 210 bar pressure, the CNG is stored in a cylinder of 25 litres in compressed format. Through the engine intake manifold, CNG was introduced in the single-cylinder diesel engine having four strokes of make Vidhata VL8. To decide the induction duration and injection start angle, a CNG injection kit was associated with an OPECU (open-loop control unit). To measure different emissions a gas analyser of AVL India having model no 444 with a gas sampler (Di), whose details are given in Table 2 is used at the exhaust pipe. Interfacing of analysers is done to an emission data acquisition platform through a serial communication bus using Rs 232 c which recorded data (emission) for 120 seconds at a 20-second interval. Electrochemical sensors (recalibrated) were used for the measurement of oxygen and NOx emissions while NDIR (non-dispersive infrared destruction principle) was used to measure CO_2, CO, and UBHC emissions. Using the reference gases the calibration has been done again for the gas analyser to ensure that the measured values come out accurate during the experiment. Finally, the mean is taken after recording double values of emission and others for all the settings. The relative humidity was recorded to be 60%, the water (cooling) temperature was recorded to be 27 ℃, and the average ambient temperature was recorded to be also at 27 ℃.

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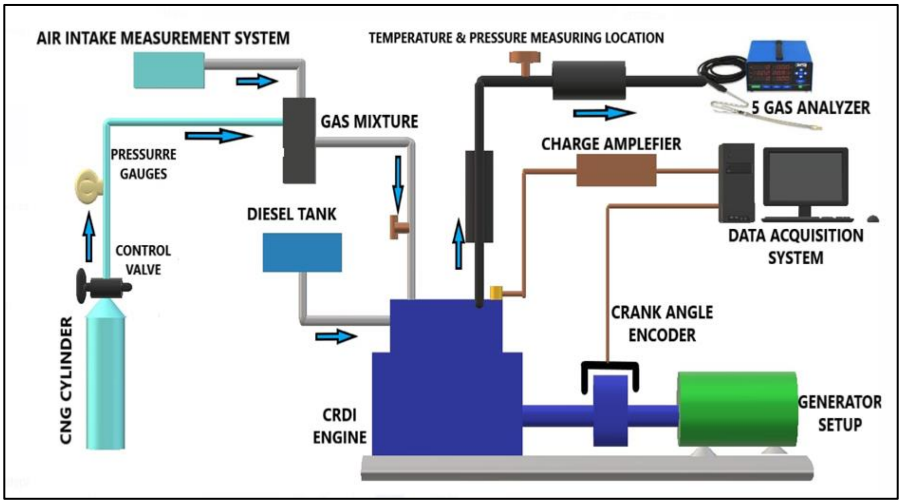

Fig. 2. Complete experimental setup.

Table 1: Engine specification

Make and type	Kirloskar, mono-cylinder, four stroke, CI engine (vertical type)
Stroke length (mm)	110
Swept volume (CC)	661
C.R. (compression ratio)	17.6
Power (kilowatts)	5.2 (1500 rpm)
Dynamometer	
Make and load measurement	Power mag and strain gauges
Type and cooling	Eddy current and Water

Table 2: Specification of the EIC

Specification	Resources
Type	Common rail injection system
Make	Bosch
Injection pressure	10 - 120 MPa
Number of holes	5 (symmetric)
Nozzle diameter	0.15 mm
Injection angle	120°

EXPERIMENTAL UNCERTAINTY ANALYSIS

The proper assessment of the investigation relies heavily on the robustness of the acquired data from the experimentation. Therefore, it is essential to evaluate the repeatability of the experimental results. To achieve this, a thorough analysis of instrumentation and sampling uncertainty was conducted. To calculate the total uncertainty associated with the measured input or output data, the root mean square method was employed, as indicated in Table 3. This comprehensive analysis ensures a thorough understanding of the repeatability and reliability of the experimental results. Table 4 demonstrates the uncertainties associated with the emission parameters considered in this study.

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Table 3: Uncertainty percentage

Name	Instrument uncertainty (%) (Ahmed and Kumar, 2016)	Calculation	Uncertainty (%)
BSFC	0.065, 1.5, 1.02	$\sqrt{(0.065)^2 + (1.5)^2 + (1.02)^2}$	1.81

Table 4: Accuracy of emission measuring instrument (AVL 444-5 gas analyzer) (Roy et al., 2014)

Parameter	Working principle	Range	Uncertainty (%)
UHC	NDIR	0 - 20,000 ppm	±0.1- ± 0.2
CO	NDIR	0 – 10 % vol	±0.2- ± 0.3
NOx	ECS	0- 5000 ppm	±0.2- ± 0.9

RESULTS AND DISCUSSION

Brake-specific fuel consumption

Fig 3 shows CNG fuel usage with Diesel+Mahua, Diesel+Ethanol+Mahua, and Diesel+Methanol+Mahua blends across various engine loads. CNG's higher heat value and efficient air-fuel mixture improve combustion, reducing BSFC. At 100% load, Diesel+Ethanol+Mahua and Diesel+Methanol+Mahua with CNG achieved 0.225 kg/kWh and 0.220 kg/kWh BSFC, respectively, with further reductions at lower loads, demonstrating enhanced fuel efficiency compared to Diesel+Mahua-CNG blends.

Hydrocarbons

Heat loss, excess fuel, and inadequate oxygen generate hydrocarbon (HC) emissions, which degrade combustion. Fig 4 shows engine-load-dependent HC emissions. Lower loads increase D+Mahua-CNG HC emissions, as shown in the graph. More HC is released as D+Mahua-CNG grows. All examined gasoline blends lower HC at higher engine loads. D+Mahua-CNG emitted substantially less HC than other blends. At 100% load, D+Ethanol+Mahua and D+Methanol+Mahua reduced HC emissions by 59.3% and 37%. Reduced 48.1% and 30.8% at 75% load, 39.3% and 21.2% at 50%. HC emissions were reduced by 33% and 19% at 25% load. D+Mahua's high viscosity inhibits the complete vaporization of larger fuel droplets, increasing cylinder fuel concentration and reducing these.

Carbon monoxide

Engine load-dependent CO emissions for different fuel blends are shown in Fig 5. Increasing engine load reduces CO emissions, given sufficient oxidation reaction temperature. Statistics show higher D+Mahua blends emit more CO. CO production depends on oxygen, reaction time, and cylinder temperature. With oxygen and reaction time, CO oxidizes to CO_2 at high in-cylinder temperatures. D+Ethanol+Mahua and D+Methanol+Mahua blends had 52.9%, 23.5%, 45.4%, 31.8%, 36%, 32%, 43.7%, and 34.3% lower CO emissions at 100%, 75%, 50%, and 25% engine loads. D+Mahua gasoline emitted 52.9% more CO at 100% load. Mahua's oxygenation lowers its calorific value and cetane number. High fuel viscosity and LHE limit atomization and vaporization. This leaves considerable combustion chamber fuel unburned, increasing CO production. CO emissions rise with D+Mahua's decreased in-cylinder temperature.

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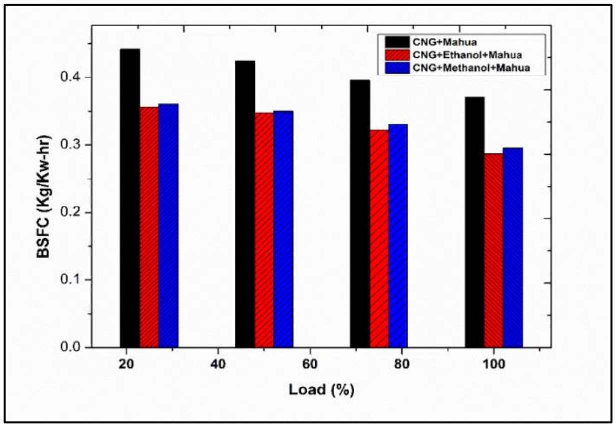

Fig. 3. Load vs. BSFC.

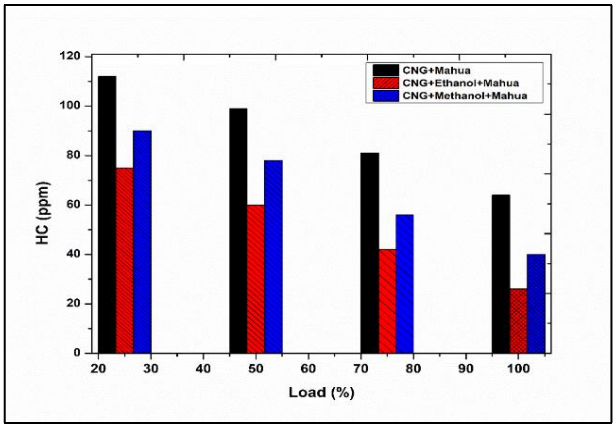

Fig. 4. Load vs. HC.

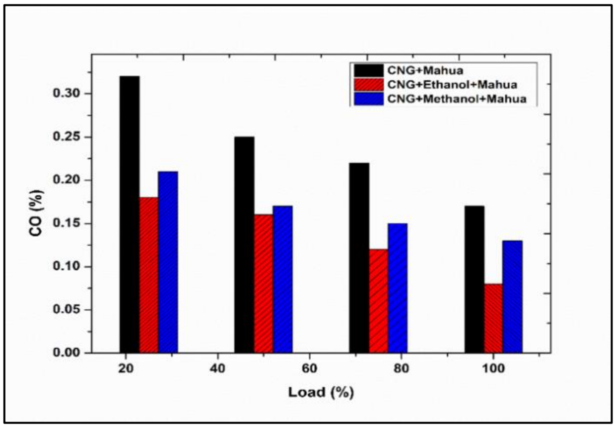

Fig. 5. Load vs. CO.

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Design of experiment

A complex calibration process is required by mostly all the parameters affecting combustion and emission characteristics which appears to generate infinite possibilities of experimental conditions for evaluation purposes, as stated by Broge (1990). Thus, for reducing the test case numbers and streamlining them, presumably in viable limits, the statistical technique used is called design of experiment (DoE) which is conducted to record and verify the outcomes of the experiment. As compared to the full factorial approach of the experiment such an attempt reduces the time as well as cost resource footprint. The process starts with the identification of output and input variables for measurement. This is widely used for studies (optimization) involving IC engines for achieving high combustion performance and low emissions.

Taguchi orthogonal array

In a limited experimental matrix, the desired response variable influence depends on many design elements, which the Taguchi technique uses an orthogonal array to study. Orthogonal arrays offer compact parameter modification matrices, minimizing experiments while maintaining effectiveness through self-balancing for scaled tests. The effects of design elements (load, fuel, injection timing, and CNG injection duration) on intended response variables of BSFC, smoke, CO, NOx, and UHC were extensively explored in this work. Three levels were allocated to each factor. When the fuel injection timing 352.5 °CA to 342.5 °CA was varied in different ways, the ranges of load were varied from 16 kg to 24 kg. As illustrated in Table 5, the CES variation was done through the three levels from 0% to 45%, 15% in each step progressively incrementing. Table 6, a 9-row Taguchi L9 orthogonal array is present in the table.

Table 5: Input parameters and levels

Parameters	Units	Level 1	Level 2	Level 3
Load	kg	16	20	24
Injection timing	°CA	352.5	347.5	342.5
Injection	μs	6300	6480	6732
Fuel	Strategy	Ethanol+CNG	Methanol+CNG	MME+CNG

Table 6: L_9 Matrix

Sl	Load (kg)	Injection timing	Duration	Fuel strategy	BSFC (Kg/Kw-hr)	Smoke (%)	CO (%)	NOx (PPM)	UHC (PPM)
1	1	1	1	1	0.71	3.83	830	283	125
2	1	2	2	2	0.69	4	800	247	127
3	1	3	3	3	0.67	4.05	970	195	149
4	2	1	2	3	0.58	4.26	870	178	91
5	2	2	3	1	0.52	4.48	900	172	86
6	2	3	1	2	0.52	4.26	830	166	73
7	3	1	3	2	0.55	4.7	920	301	71
8	3	2	1	3	0.46	4.48	710	293	69
9	3	3	2	1	0.50	3.83	560	273	66

Experimental data analysis

The measured performance characteristic evaluates parameter influence once the experimental design is established. Thus, for every experiment conducted, the SN number (S/N ratio) (Table 7) has to be computed to determine the effect of each variable. The system will be more robust depending on the higher value of the S/N ratio. While analysing the S/N ratio, three categories of performance characteristics come into the picture namely, the nominal-the-better, the higher-the-better, and the lower-the-better. For UHC, NOx, CO, smoke, and BSFC, smaller-is-better applies (Equation (2)).

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$$\text{Smaller-the-better} = S/N = -10\,\mathrm{Log}\frac{\sum_{i=1}^{n}\frac{1}{y_i^2}}{n} \tag{2}$$

where n is measurements and y is ith value.

Table 7: S/N ratio for different engine output

Experiment no.	SN (BSFC)	SN (smoke)	SN (CO)	SN (NOx)	SN (UHC)
1	2.93821	-11.6640	-58.3816	-49.0357	-41.9382
2	3.21044	-12.0412	-58.0618	-47.8539	-42.0761
3	3.42680	-12.1491	-59.7354	-45.8007	-43.4637
4	4.62724	-12.5882	-58.7904	-45.0084	-39.1808
5	5.54732	-13.0256	-59.0849	-44.7106	-38.6900
6	5.59681	-12.5882	-58.3816	-44.4022	-37.2665
7	5.19275	-13.4420	-59.2758	-49.5713	-37.0252
8	6.65094	-13.0256	-57.0252	-49.3374	-36.7770
9	5.96864	-11.6640	-54.9638	-48.7233	-36.3909

Grey-Taguchi approach

Deng (1989) proposed converting multi-response to single-response optimization. As shown in Equation (3) for Grey relational generation, the normalization was done by making use of lower-the-better characteristics for the S/N Ratio in the Grey relational analysis.

$$y_i(p) = \frac{\max z_i(p) - z_i(p)}{\max z_i(p) - \min z_i(p)} \tag{3}$$

For the pth response, max $zi(p)$ and min $zi(p)$ are its highest and smallest values. Table 8 summarizes the data (normalized) after Grey relational generation.

Table 8: Grey relation generation

Experiment no.	BSFC	Smoke	CO	NOx	UHC
1	1.000	0.000	0.716	0.896	0.784
2	0.927	0.212	0.649	0.668	0.804
3	0.868	0.273	1.000	0.271	1.000
4	0.545	0.520	0.802	0.117	0.394
5	0.297	0.766	0.864	0.060	0.325
6	0.284	0.520	0.716	0.000	0.124
7	0.393	1.000	0.904	1.000	0.090
8	0.000	0.766	0.432	0.955	0.055
9	0.184	0.000	0.000	0.836	0.000

The correlation between the optimal and normalized results is demonstrated by computing the GRC using Equation (4), as presented in Table 9.

$$\xi_i(p) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{0i}(p) + \psi\Delta_{\max}} \tag{4}$$

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where $\Delta_{0i} = \|y_0(p) - y_i(p)\|$ = Absolute value $y_0(p)$ and $y_i(p)$; φ is the coefficient $0 \leq \varphi \leq 1$ (0.5) (Ahmed and Kumar, 2016), and $\Delta_{\max} = \forall j^{\max} \in i \forall p^{\max} \| y_0(p) - y_i(p) \|$ the largest value of Δ_{0i}.

$\Delta_{\min} = \forall j^{\min} \in i \forall p^{\min} \| y_0(p) - y_i(p) \|$ Smallest value of Δ_{0i}.

Grey relation coefficient $\xi_i(p)$

Table 9: Grey relation coefficient (performance characteristic)

Experiment no.	BSFC	Smoke	CO	NOx	UHC
1	1.000	0.333	0.638	0.828	0.699
2	0.872	0.388	0.588	0.601	0.718
3	0.792	0.407	1.000	0.407	1.000
4	0.524	0.510	0.716	0.362	0.452
5	0.416	0.681	0.786	0.347	0.426
6	0.411	0.510	0.638	0.333	0.363
7	0.452	1.000	0.838	1.000	0.355
8	0.333	0.681	0.468	0.917	0.346
9	0.380	0.333	0.333	0.753	0.333

As per Ahmed and Kumar (2016), for a single response, if the optimum normalized value is close to the corresponding experimental result then, it is implied from Grey relational coefficients high value. Using Equation (5), the overall Grey relational grade is computed. Roy et al. (2014) concluded high desirability comes from a high Grey relational grade value.

$$\delta_i = \sum_{p=1}^{n} w_p \xi_i(p), \text{ n=1-3} \tag{5}$$

It implies the sum of w_p equals to 1 where w_p is the weighting value for each Grey relational coefficient (zero to one) and *n* is the number of output responses. For the response variables UHC, NOx, CO, smoke, and BSFC, 0.33 (w_3), 0.33 (w_2), and 0.33 (w_1), respectively were assigned as weighting factors in this study. The weightage factor varies per the engine designer's objectives.

Table 10 shows grey grades for L9 experiments. It is clear from the table that a high GRG corresponds to a high value of the S/N ratio as it comes closer to the ideal S/N ratio. Thus, to run the perfect strategy to acquire the best solution of multiple objectives system, the seventh experimental run gains the highest GRG and can subsequently be regarded as the best experimental sequence, as the results conclude.

Table 10: Grey relation grade

Experiment no.	Grey relation grade (GRG)	Rank
1	0.700	3
2	0.633	4
3	0.721	2
4	0.513	7
5	0.531	6
6	0.451	8
7	0.729	1
8	0.549	5
9	0.427	9

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Analysis of S/N ratio

Table 10 presents Grey relational grades analyzed using the S/N Ratio method, applying the "higher-the-better" criterion to determine the optimal factor levels (Equation (6)).

$$S / N = -10 \log \left[\frac{1}{N_i} \sum_{u=1}^{N_i} \frac{1}{y_u^2} \right] \quad (6)$$

Ni is the trial count, *u* is the trial number, and *i* the experiment, analyzed using MINITAB (Table 11). From Table 11, it is distinctly observed that rank 1 is evaluated based on the highest S/N ratio, held by the input factor of load and then followed by injection duration, injection timing, and fuel strategy as rank 2, 3, and 4, respectively. The ranks signify the relative degree of influence or effects of the input factors on the output results.

Table 11: Grey-fuzzy logical grade response table

Factors	L-1	L-2	L-3	Delta	Rank
Load	-3.303	-6.071	-5.118	2.768	1
Injection timing	-3.883	-4.89	-5.718	1.834	3
Injection duration	-5.074	-5.723	-3.694	2.028	2
Fuel strategy	-5.333	-4.542	-4.616	0.791	4

For the selected design factors (load, injection timing, duration, and fuel strategy), the presentation of S/N ratios is shown in Fig 6. The optimal process parameter combination was found $A_1B_1C_3D_2$, wherein the load is 16 kg, injection timing is 352.50 °CA, and injection duration is 6732 µs with fuel blend as CNG and methanol. Among these, the most contributing factor is load which can be suggested from Table 11.

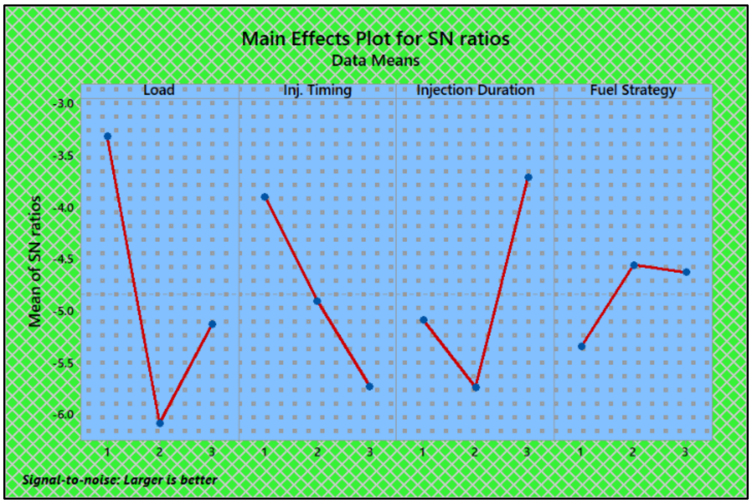

Fig. 6. Response -GRG.

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CONCLUSIONS

The study aimed to optimize the emission and performance parameters of an internal combustion (IC) engine by integrating Taguchi's method with grey relational analysis. Through the application of Taguchi's L9 orthogonal array, a minimal number of experimental trials were required to systematically investigate the effects of load, injection timing, duration, and fuel strategy.

(i) The optimal process parameters determined from the experiment were a load of 16 kg, an injection timing of 352.50 °CA, and an injection duration of 6732 μs, using a fuel blend of CNG and methanol.

(ii) Among the factors studied, engine load was identified as having the most significant impact on reducing specific fuel consumption and emissions, including smoke, CO, NOx, and UHC.

(iii) This optimization method, validated through analysis in an unmodified IC engine, provides a robust framework for improving engine performance and reducing emissions, aligning with the overarching goals of the project.

The conclusions drawn reflect the systematic approach and the effectiveness of the proposed algorithm in achieving these objectives.

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CONFLICT OF INTEREST STATEMENT

The authors confirm no self-benefits, financial conflicts, or conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: experimental analysis, procedure, and writing: Dr. Jibitesh, Prof. Jun Peng, Dr. Payel; conceptualization, procedure: Dr. Rajesh and Mr. Srikanth; drafting and revising: Dr. Niraj, Dr. Nikhil and Ms. Shweta. All authors reviewed the results and approved the final version of the manuscript.

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