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Modelling and Performance Optimization of a Dual Fuel Mode Power Generation System (A Case Study of *Allanblackia floribunda* Seed Oil)

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Abstract
This study focuses on the optimization of a small-scale, spark-ignition power generation system operating on a dual fuel arrangement of petrol and Liquefied Petroleum Gas (LPG) The research addresses the challenge of calibrating such systems for optimal performance, which volves balancing often conflicting objectives like fuel efficiency, power output, and emissions A Response Surface Methodology (RSM) framework, employing a Central Composite Design (CCD) of experiments, was used to investigate the effects of five key operating parameters Engine Load, Generator Speed, Ignition Timing, Air-Fuel Ratio, and Compression Ratio Empirical quadratic models were developed and validated to predict key responses Brake Thermal Efficiency (BTE), Specific Fuel Consumption (SFC), Carbon Monoxide (CO), and Nitrogen Oxides (NOx) emissions, and Power Output The Desirability Function Approach was then applied for multi-response optimization to identify the bestcompromise operating conditions for both petrol and LPG modes. The results demonstrate that while both fuels can achieve nearly identical thermal efficiency at their respective optima, LPG operation enables a 22 9% higher power output. However, this is accompanied by a 5.56% increase in mass-based fuel consumption and significant increases in CO (66.2%) and NOx (14.1%) emissions under the high-load optimization strategy The study concludes that LPG is a superior fuel for applications demanding high power density, provided that the increased emissions are managed through targeted calibration or after-treatment, the Allanblankia florrbunda Seed Oil was used as case study, thereby offering a viable path for cleaner and more powerful decentralized electricity generation.

***Keywords**: Modeling; Optimization; Performance, Allanblackia floribunda Seed Oil.*

1.0 Introduction

Access to affordable, reliable and clean small-scale electric power remains a challenge in many developing and peri-urban communities. Portable spark-ignition generators fuelled by petrol are widely used because of their low capital cost and simplicity; however, high operating expenses and local air pollution are significant drawbacks [1].

Liquefied petroleum gas (LPG) offers attractive properties as a complementary fuel for these engines, including a high octane number, wide flammability limits and cleaner combustion that can reduce CO and HC emissions [2], [3]. Dual-fuel petrol–LPG operation can therefore lower fuel cost per kilowatt-hour and local pollution, yet the gaseous nature of LPG may reduce volumetric efficiency and peak power unless intake and ignition parameters are carefully adjusted [1]. The net performance depends on interacting factors such as LPG energy share, engine load, air–fuel ratio and ignition timing, making systematic modelling and multi-response optimisation essential.

Response surface methodology with central composite design (RSM–CCD) provides an efficient framework for building quadratic surrogate models of engine behaviour [4]. When multiple responses (brake thermal efficiency, fuel consumption, CO and HC emissions) must be considered together, the desirability-function approach enables multi-objective optimisation to identify practical trade-off settings [5], [6]. This paper applies RSM–CCD and desirability analysis to model and optimise the performance of a dual-fuel petrol–LPG power generation system.

1.1 Aim and Objectives of the Study

This work aims to develop validated empirical models and identify multi-response optimum operating settings for a petrol-LPG dual-fuel power generation system, using Response Surface Methodology (RSM) with a Central Composite Design (CCD) experimental plan and the Desirability Function approach for multi-objective optimisation.

The study will be guided by the following three objectives

1. To establish empirical RSM models that relate the primary input factors to key responses (brake thermal efficiency, brake specific fuel consumption, CO and NOx emissions and power output).

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2. To implement a Central Composite Design (CCD) to obtain statistically efficient experimental data and use ANOVA to identify significant main effects and interactions
3. To determine practical multi-response optimum operating conditions using the Desirability Function approach and validate the predicted optimum through additional experimental runs or validated simulation.

1.2 Statement of the Problem

Although LPG substitution in SI engines is widely studied, outcomes reported in the literature vary with engine design, LPG introduction method (carburetted, vapour-injection, liquid injection), and operating conditions Some studies report reductions in CO and HC but also reductions in volumetric efficiency and power output at high LPG shares, others observe increased NOx formation at higher combustion temperatures when ignition timing is advanced to recover power [1], [2]. For small petrol generators commonly used for off-grid and backup power few studies present an integrated experimental-statistical framework that quantifies interactions among LPG share, load and ignition timing, and which then uses multi-response optimisation to provide a single practical calibration for real-world use The lack of such a validated RSM-CCD-Desirability framework means end users and retrofit kit suppliers still rely on empirical tuning and trial-and-error, risking sub-optimal fuel economy, inconsistent power delivery or unintended emission increases.

Therefore, there is a need to produce validated empirical models that (a) quantify how LPG fraction, engine load and ignition timing interact to affect performance and emissions, and (b) identify a compromise operating setting (or small set of settings) that balances efficiency, fuel consumption and emissions for typical small generator use. Achieving this will make LPG retrofits more reliable and support broader adoption where cost and emissions are critical.

2.0 Literature Review

Concept and Principles of Dual-Fuel SI Engines

Dual-fuel spark-ignition (SI) engines are a specialized category of internal combustion engines designed to operate on a mixture of a primary liquid fuel, typically petrol, and a secondary gaseous fuel, most commonly liquefied petroleum gas (LPG) or compressed natural gas (CNG) This dual-fuel strategy was developed to address both economic and environmental challenges associated with conventional petrol engines, such as high fuel costs, fluctuating supply, and pollutant emissions [8]. In these engines, the liquid fuel generally serves as a pilot for ignition, while the gaseous fuel contributes most of the energy content. This dual-fuel approach combines the reliable ignition characteristics of petrol with the high-octane number and clean-burning properties of gaseous fuels. From a combustion perspective, dual-fuel operation offers significant thermodynamic advantages. LPG, for example, has a high hydrogen-to-carbon ratio and low carbon content, which reduces soot formation and promotes cleaner combustion [9]. Its high volatility ensures rapid vaporization and thorough mixing with intake air, resulting in a more homogeneous mixture within the cylinder. This homogeneity allows for more stable flame propagation, smoother in-cylinder pressure rise, and improved heat-release characteristics, which collectively enhance engine efficiency Additionally, the high-octane number of LPG provides higher knock resistance, allowing the engine to operate at more advanced ignition timings without the risk of premature detonation [10].

2.1 Performance, Emission, and Operational Considerations

Dual-fuel SI engines offer tangible improvements in performance and emission characteristics when compared to conventional petrol-only engines. Moderate LPG substitution ratios, often between 40% and 60% of total fuel energy, have been shown to increase brake thermal efficiency by 5-10% and reduce carbon monoxide (CO) and unburned hydrocarbon (HC) emissions [2]. LPG's cleaner combustion results from the more uniform mixture and the lower flame temperature in some regions of the cylinder, which also contributes to a reduction in particulate matter formation. Nitrogen oxides (NOx) emissions, however, are sensitive to cylinder temperature and equivalence ratio. The improved mixture homogeneity provided by LPG generally lowers local peak temperatures, which can reduce NOx formation under optimized conditions [11].

Operational flexibility is another key advantage of dual-fuel SI engines. The ability to switch or blend fuels depending on availability and cost makes these engines particularly suitable for small-scale power generation, backup generators, and domestic or commercial cogeneration applications. This flexibility also supports energy security in regions where LPG is abundant and inexpensive compared to petrol. Furthermore, dual-fuel engines can operate efficiently over a wide range of loads and speeds, making them suitable for applications that demand varying power output [8]. Despite these advantages, dual fuel engines face some technical challenges The correct air fuel mixture distribution is crucial to prevent misfire or incomplete combustion, particularly at high LPG substitution ratios. The injection or mixing system must ensure adequate vaporization and even distribution of the gaseous fuel Ignition timing also requires careful adjustment because the combustion characteristics differ from petrol-only operation. Research has shown that optimal ignition timing is usually slightly advanced

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compared to conventional petrol engines to fully exploit the high knock resistance of LPG [9]. Thermodynamically, dual-fuel engines benefit from the higher specific energy of LPG per unit mass and its favorable stoichiometric ratio.

2.2 Review of Petrol-LPG Dual-Fuel Engine Studies

Petrol-LPG dual-fuel engines have been extensively studied over the last decade due to their potential for reducing fuel costs, enhancing thermal efficiency, and mitigating harmful emissions. Research has consistently demonstrated that the substitution of petrol with LPG in spark-ignition engines leads to distinct improvements in engine performance and emission characteristics, although these effects are highly dependent on the LPG substitution ratio, operating load, ignition timing, and engine configuration. Early investigations focused on small-scale generators and automotive engines, examining performance metrics such as brake thermal efficiency, brake-specific fuel consumption (BSFC), exhaust gas emissions, and combustion stability [10], [12].

Several experimental studies have reported that moderate LPG substitution ratios (typically 40-60% of total fuel energy) result in significant reductions in carbon monoxide (CO) and bumed hydrocarbons (HC) [2] evaluated a single-cylinder St engine under various LPG petrol blending ratios and found that at 50% LPG substitution, CO emissions decreased by approximately 22% compared to petrol-only operation, while HC emissions were reduced by 18%. This improvement is attributed to the higher hydrogen-to-carbon ratio in LPG, which promotes more complete combustion and enhances flame propagation, leading to more uniform heat release across the cylinder

Studies also highlight the influence of dual-fuel operation on nitrogen oxide (NOx) formation.

Although LPG can lower peak local temperatures due to better mixture homogeneity, the overall effect on NOx depends on engine load and equivalence ratio. Altun et al. [11] used optical diagnostics to demonstrate that under partial load conditions, NOx emissions decreased with LPG substitution, while under high-load conditions, the NOx levels could increase slightly due to higher overall combustion temperatures. This emphasizes the need for careful optimization of engine operating parameters to maximize environmental benefits while maintaining performance.

Performance analysis has also focused on brake thermal efficiency (BTE) and fuel consumption. Arabacı [9] observed that dual-fuel S1 engines operating with 40-60% LPG substitution exhibited an increase in BTE by 4-8% compared to petrol-only operation. The improved efficiency is attributed to the high-octane number of LPG, which allows for more advanced ignition timing without knock, and the enhanced volumetric efficiency due to faster vaporization and homogeneous air-fuel mixing. However, excessive LPG substitution can lead to reduced power output, particularly at high engine speeds, because the gaseous fuel occupies space in the intake manifold, displacing air and reducing the effective charge [12].

In addition to laboratory-scale experiments, numerical modelling and simulation studies have provided valuable insights into dual-fuel engine behaviour, Hosseini et al. [8] developed a detailed thermodynamic model for LPG-petrol dual-fuel combustion and validated it against experimental data. Their results showed close agreement with measured performance parameters and highlighted the sensitivity of engine efficiency and emissions to LPG substitution ratio, spark timing, and air-fuel ratio. Such modelling studies are crucial for identifying optimal operating conditions before experimental implementation, reducing time and cost associated with engine testing.

2.3 Modelling Approaches for Dual Fuel Spark Ignition Engines

Thermodynamic and Zero-Dimensional Models

Thermodynamic and zero-dimensional models form the foundation of dual-fuel engine modelling. These models treat the combustion chamber as a single control volume, where pressure, temperature, and heat release are computed as functions of crank angle and time They are particularly useful for predicting in-cylinder pressure and overall engine performance without requiring computationally intensive simulations [13]. In dualfuel St engines, thermodynamic models often incorporate the effects of fuel composition, air-fuel ratio, and pilot injection timing. For example, LPG-petrol mixtures are modelled by considering their respective lower heating values, stoichiometric ratios, and ignition delays.

Hosseini et al. [8] demonstrated that such models can accurately predict brake thermal efficiency, peak pressure, and heat release profiles for different LPG substitution ratios, providing insights into optimal engine operating conditions.

Despite their simplicity, zero-dimensional models are limited in capturing local in-cylinder phenomena such as turbulence, flame propagation, and mixture stratification. However, they are highly effective for preliminary engine design, optimization studies, and sensitivity analyses, making them an ideal tool for the initial phases of dual-fuel engine research [10].

Multi-Zone and Quasi-Dimensional Models

To overcome the limitations of zero-dimensional models, researchers often employ multi-zone or quasidimensional models. These divide the combustion chamber into several zones typically unburned, burned, and partially burned regions to more accurately simulate flame propagation, heat transfer, and chemical kinetics [9]. In dual-fuel engines, multi-zone models are particularly valuable because they capture the distinct combustion characteristics of petrol and LPG within the same chamber. Parameters such as flame speed, ignition delay, and temperature distribution can be evaluated for different fuel ratios and engine loads, providing a more realistic representation of engine behaviour

Quasi-dimensional models also incorporate simplified turbulence models to estimate the effects of in-cylinder mixing and swirl on combustion. Studies have shown that such models can accurately predict not only performance parameters but also emissions of CO, HC, and NOx under various dual-fuel operating conditions. Zeng et al. [12] applied a multi-zone approach to simulate LPG-petrol dual-fuel combustion and found strong agreement with experimental data, highlighting the utility of these models for optimization studies.

2.4 Response Surface Methodology in Engine Optimization

Concept and Fundamentals of Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is a robust statistical and mathematical tool used to model, analyze, and optimize complex processes in which multiple input variables affect one or more output responses RSM integrates principles from design of experiments (DoE), regression analysis, and optimization to develop empirical models that approximate the functional relationships between independent variables (factors) and dependent variables (responses) [14]. In internal combustion engines, especially dual-fuel spark-ignition (SI) engines, numerous factors influence performance and emissions simultaneously These include LPG substitution ratio, spark timing, air-fuel equivalence ratio, engine speed, and load. Because these factors often interact in a non-linear manner, RSM provides a systematic approach for exploring the design space efficiently and predicting optimal operating conditions.

The primary goal of RSM is to determine the relationship between the responses and input variables, identify the combination of variables that optimize engine performance, and evaluate the sensitivity of each factor. A second-order polynomial equation is commonly used to approximate the response surface:

$$Respons(Y) = \beta 0 + \sum \beta AXI + \sum \beta . XA + \sum\sum \beta OXIXO + \varepsilon \quad (1)$$

Where:
Y-response variable (eg., brake thermal efficiency, CO emission)
X XO independent variables (eg., LPG fraction, ignition timing)
Bo intercept
B. B, B. coefficients for linear, quadratic, and interaction terms experimental
error

This equation allows researchers to approximate the response surface in the multidimensional design space, enabling prediction, visualization, and optimization of engine parameters [15].

Application of RSM in Dual-Fuel Engine Studies

In petrol-LPG dual-fuel engines, RSM has been widely employed to optimize multiple performance and emission parameters simultaneously Independent variables often include LPG energy fraction, spark timing, compression ratio, engine load, and air-fuel ratio, while dependent responses include brake thermal efficiency, brake-specific fuel consumption (BSFC), power output, CO, HC, and NOx emissions Conventional one-factorat-a-time (OFAT) approaches fail to capture the interactive effects of these parameters, whereas RSM provides a structured framework for investigating these interactions while reducing the total number of experimental runs [2].

For example, Hashem et al. [2] studied a single-cylinder dual-fuel S1 engine with LPG-petrol blends. Using RSM, they developed regression models describing the effect of LPG substitution ratio, spark timing, and engine load on brake thermal efficiency and emissions.

The response surface plots clearly demonstrated the combined effects of these variables, revealing an optimal operating region where thermal efficiency was maximized, and CO and HC emissions were minimized. Similarly, Zeng et al. [12] applied RSM to explore the interactions between LPG fraction and ignition timing, showing that moderate LPG substitution ratios improved engine efficiency while reducing CO emissions, but excessive substitution led to increased HC and reduced volumetric efficiency

RSM also facilitates sensitivity analysis, enabling researchers to identify which input parameters have the most significant impact on engine responses. In dual-fuel engines, this is particularly valuable because the substitution of LPG alters combustion dynamics, in-cylinder temperature, and flame propagation. By evaluating the significance of each factor through analysis of variance (ANOVA), researchers can focus optimization efforts on critical variables, thereby improving both engine efficiency and emissions simultaneously [9].

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2.5 Central Composite Design (Ccd) As an Experimental Design Tool

The Central Composite Design (CCD) is a cornerstone of Response Surface Methodology (RSM), widely used in experimental research to study complex, multivariable systems. Its key advantage lies in estimating not only linear and interaction effects but also quadratic (curvature) effects, which is critical when system responses are nonlinear. In dual-fuel spark-ignition engines, CCD enables robust modelling, optimization, and prediction while minimizing the number of experimental runs required, making it a cost-effective and scientifically sound approach [15].

2.5.1 Structure and Rationale of CCD

A classical CCD consists of three categories of points:
1 Factorial (corner) points. Capture main effects and two-factor interactions at high and low factor levels
2. Axial (star) points Located outside factorial extremes, allowing estimation of curvature
3. Center points. Mid-level runs, often replicated to assess experimental error and detect curvature
For k continuous factors, the total number of experimental runs is:

$$N = 2k + 2k + n_0 \tag{2}$$

where:

N= Total number of experimental runs
k= Number of continuous factors
n_0= Number of center points

where factorial points, axial points, and center-point replicates make the design efficient, compared with full three-level factorial designs, CCD requires far fewer runs while still supporting second-order modelling [15]. This is especially advantageous in dual-fuel engine research, where each experiment consumes time, fuel, and other resources Variants of CCD include rotatable, face-centered, and spherical designs, each with subtle differences in axial point placement. Rotatable CCDs maintain uniform prediction variance in all directions from the center, while face-centered CCDs simplify experimentation by setting dual points at the factorial levels [15]. Selecting the appropriate variant ensures experimental efficiency without compromising model accuracy.

2.6 Desirability Function Approach for Multi-Response Optimization

Optimization of engineering systems often involves multiple, sometimes conflicting responses. In dual-fuel spark-ignition engines, key performance indicators such as brake thermal efficiency, specific fuel consumption, and exhaust emissions must be considered simultaneously. The Desirability Function Approach (DFA) is a widely accepted method for multi-response optimization, allowing these different objectives to be transformed into a single scalar function that can be maximized to identify optimal operating conditions [15], [16].

Concept of the Desirability Function

Optimization involving multiple output variables is a common challenge in engineering. manufacturing, product development, and quality improvement. Traditional optimization techniques often struggle when responses conflict, improving one variable may worsen another. The Desirability Function (DF) approach provides a practical and intuitive framework for transforming multiple responses into a single composite measure of "desirability," enabling simultaneous multi-response optimization [15], [16].

Origin and Evolution of the Desirability Concept

The DF concept can be traced to early work by Harrington [17], who first introduced the idea of converting responses into a scale of desirability ranging from completely unacceptable to fully ideal Building on this foundation, Derringer and Suich [16] formalized a more flexible and widely applicable version of desirability functions. Their method allowed practitioners to tailor desirability definitions to different response types such as "larger is better, smaller is better or target is best making the method suitable for diverse optimization problems. The desirability function (DF) approach has become popular for its simplicity and flexibility. Unlike more complex multi-objective optimisation methods, it converts technical specifications into practical, easy-to-interpret scales that reflect engineering judgment [18].

3.0 Materials and Methods

3.1 Experimental Setup and Apparatus

The experimental setup for this study consists of a FIRMAN 6000 series spark-ignition engine configured for dual-fuel operation (Petrol-LPG) and coupled to a 50 Hz power generation system. The engine has an approximate rated output of 11-12 kW (=15 HP) at a rated speed of 1500 rpm, suitable for small-scale electricity generation. The setup is designed to evaluate the performance and emissions of a Sequential Vapour Phase Injection (SVPI) dual-fuel system, with LPG as the primary fuel and petrol as the secondary/backup fuel.

A. Engine and Power Generation System

a. Engine Model. FIRMAN 6000 series, single-cylinder, spark-ignition engine
b. Rated Power 11-12 kW (15 HP)
c. Rated Speed: 1500 rpm for 50 Hz power generation.
d. Ignition System Spark ignition with original petrol engine ECU.
e. Load Application. The engine drives a 50 Hz alternator connected to a controlled resistive load bank to simulate various electrical loads.

Dual-Fuel System Configuration

The dual-fuel system operates on the Sequential Vapour Phase Injection (SVPI) principle, designed to maximize the use of LPG while retaining petrol as a backup fuel during start-up.

a. Primary Fuel: LPG (used predominantly during operation)
b. Secondary Fuel Petrol (used during engine start-up and transient conditions).
c. Control System: A dedicated LPG Electronic Control Unit (ECU) integrated with the engine's original management system ensures proper fuel sequencing and injection timing.

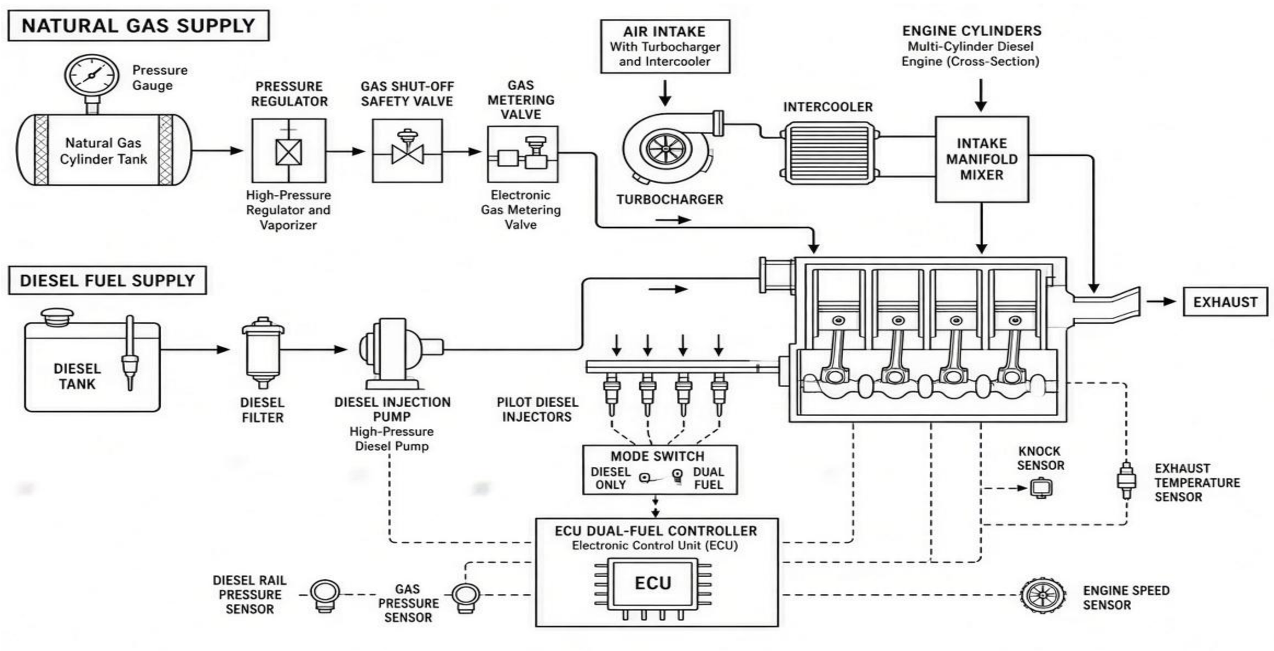

Figure 1: schematic drawing of the dual-fuel system (*Allanblanckia floribunda* seed oil)

B. Dual-Fuel System Configuration

The dual-fuel system operates on the Sequential Vapour Phase Injection (SVPI) principle, designed to maximize the use of LPG while retaining petrol as a backup fuel during start-up.

a. Primary Fuel: LPG (used predominantly during operation)
b. Secondary Fuel Petrol (used during engine start-up and transient conditions).
c. c Control System: A dedicated LPG Electronic Control Unit (ECU) integrated with the engine's or
d. Fuel Delivery: Liquid LPG is drawn from the cylinder, converted to vapour via a heated regulator, and injected sequentially into the intake ports of the engine The SVPI system ensures each cylinder receives the correct air-fuel mixture to optimize combustion efficiency and minimize emissions.

C. Instrumentation and Measurement Devices

The setup is fully instrumented to monitor performance and emissions under varying operating conditions. Key instruments include

a. a Fuel Flow Meters: Separate meters for LPG and petrol to measure consumption accurately
b. Torque and Speed Sensors: Connected to a dynamometer for measuring engine output.
c. Exhaust Gas Analyzer. Measures CO, CO_2, and HC emissions.
d. Temperature and Pressure Sensors Installed at the cylinder head and exhaust for performance monitoring

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e. e Data Acquisition System (DAQ). Multichannel DAQ system records sensor data in real-time for subsequent modelling and optimization.

D. Experimental Arrangement

The engine is mounted on a rigid test frame with the alternator coupled directly to the crankshaft. LPG and petrol supply lines are routed safely, with solenoid valves and pressure regulators to ensure controlled fuel delivery. Sensors and measurement devices are calibrated prior to experimentation to ensure data reliability. The DAQ system interfaces with mini-tab and Design-Expert software to facilitate real-time data logging and subsequent RSM-based modelling and optimization.

3.2 Experimental Design (Design of Experiments - Doe)

To systematically investigate the performance and emissions of the dual-fuel (Petrol-LPG) power generation system, a Design of Experiments (DoE) approach was adopted. The DoE enables efficient exploration of multiple factors and their interactions, facilitating the development of predictive models for optimization.

Selection of Independent Variables (Factors)

The key independent variables (factors) influencing engine performance and emissions were carefully selected based on literature review and preliminary trials. These factors are summarized in Table 1.

Table 1: Key Independent Variables (factors)

Factor	Symbol	Units	Range/Levels
Engine Load	EL	kW	25-100% of rated load
Generator Speed	GS	rpm	1200-1800
Ignition Timing	IT	°BTDC	15-30
Air-Fuel ratio	ATR	-	12:1-18:1
Compression Ratio	CR	-	8.5-10.5

These factors were chosen because they significantly affect combustion efficiency, fuel consumption, and emissions in dual-fuel engines.

Selection of Dependent Variables (Responses)

The dependent variables (responses) represent the measurable outputs of the system, capturing both performance and emission characteristics. The responses modeled in this study are listed in Table 2.

Table 2: Dependent variables (Response)

Response	Symbol	Units	Description
Brake thermal efficiency	BTE	%	Efficiency of converting fuel energy to mechanical work
Specific Fuel consumption	SFC	kg/kwh	Fuel consumed per unit of energy input
Carbon Monoxide Emission	CO	%Vol	Indicator of complete combustion
Nitrogen Oxide Emission	NOx	ppm	Indicator of high temperature combustion and pollutant formation
Power Output	PO	kW	Mechanical Power delivered by the engine

Experimental/Test Matrix

To systematically investigate the effect of the key operating parameters on the system's performance and emissions, a structured Design of Experiments (DoE) approach was employed. A Central Composite Design (CCD) under the Response Surface Methodology (RSM) framework was selected for this study. The CCD is highly efficient for fitting second-order polynomial models and is ideal for estimating the interaction and quadratic effects between factors, which are crucial for a comprehensive optimization study.

Five independent variables were identified as critical factors influencing the generator's output: Engine Load (X_1), Generator Speed (X_2), Ignition Timing (X_3), Air-Fuel Ratio (X_4), and Compression Ratio (X_5). The practical high and low levels for each factor were determined based on the engine's operational manual, preliminary tests, and engineering judgment to ensure they represented a realistic and safe operating envelope for a stationary power generator.

The defined factor levels for the two distinct fuel modes are presented in Tables 3 and 4.

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The use of coded values (-1 for low, +1 for high, and 0 for the center point) simplifies the mathematical modeling process and allows for a direct comparison of the effect of each factor, irrespective of their different physical units.

Table 3: Limits of the Independent variables

S/N	Factor Description	Coded Symbols	Factor Values	
			Low (-1)	High (+1)
1	Engine Load (kW)	X_1	2.24	11.19
2	Generator Speed (rpm)	X_2	2800	3200
3	Ignition Timing (°BTDC)	X_3	15	35
4	Air-Fuel Ratio (AFR)	X_4	12:1	16:1
5	Compression Ratio (CR)	X_5	8:1	10:1

Table 4: Limits of the Independent variables for LPG

S/N	Factor Description	Coded Symbols	Factor Values	
			Low (-1)	High (+1)
1	Engine Load (kW)	X_1	2.24	11.19
2	Generator Speed (rpm)	X_2	2800	3200
3	Ignition Timing (°BTDC)	X_3	16	36
4	Air-Fuel Ratio (AFR)	X_4	14:1	17:1
5	Compression Ratio (CR)	X_5	8.5:1	11:1

The CCD for this five-factor study generated a comprehensive test matrix comprising factorial points, axial points, and center points. This structure ensures a robust dataset for modeling the response surfaces. The complete experimental design, showing the coded values for all 33 unique experimental runs for each fuel, is detailed in Tables 5.

Table 5: Response Surface Design layout showing coded and natural factors for LPG Experimental Runs

Std Order	Run Order	Engine load	Gen. Speed	Ignition Timing	AFR	CR	BTE	SFC	CO Emission	NOx Emission	Power Output
1	1	0	0	0	0	0	29.4	0.39	0.82	610	6.7
2	2	-1	-1	-1	-1	-1	22.3	0.52	2.1	720	2.2
3	3	1	-1	-1	-1	-1	28.1	0.36	0.64	410	11.4
4	4	-1	1	-1	-1	-1	32.2	0.31	0.47	880	2.1
5	5	1	1	-1	-1	-1	24.2	0.49	1.25	580	2.3
6	6	-1	-1	1	-1	-1	21.1	0.54	2.3	390	2.1
7	7	1	-1	1	-1	-1	25.7	0.41	1.95	510	10.9
8	8	-1	1	1	-1	-1	29.5	0.39	0.82	610	6.7
9	9	1	1	1	-1	-1	30.9	0.33	0.82	850	11
10	10	-1	-1	-1	1	-1	29.4	0.39	0.59	610	6.7
11	11	1	-1	-1	1	-1	21.6	0.53	2.05	400	2
12	12	-1	1	-1	1	-1	29.5	0.39	0.82	610	6.7
13	13	1	1	-1	1	-1	23.5	0.54	1.8	830	11.19
14	14	-1	-1	1	1	-1	28.5	0.37	1.22	670	11.3
15	15	1	-1	1	1	-1	30.2	0.34	1.05	730	11.1
16	16	-1	1	1	1	-1	21.7	0.53	2.15	400	2.1
17	17	1	1	1	1	-1	31	0.32	1	900	11.4
18	18	0	0	0	0	0	29.4	0.39	0.82	610	6.7
19	19	-1	1	1	1	0	23.6	0.5	1.45	530	6.7
20	20	0	-1	0	0	0	27.9	0.41	0.82	610	6.7
21	21	-1	-1	0	0	0	25.6	0.5	1.95	530	2.24
22	22	-1	0	0	0	0	23.1	0.51	1.52	520	2
23	23	0	0	-1	0	0	31.6	0.31	0.72	910	11
24	24	0	0	0	-1	0	30.1	0.38	0.78	560	6.6
25	25	0	0	0	0	0	27.8	0.41	0.95	570	6.4
26	26	0	0	0	0	0	27.9	0.42	0.6	870	6.8
27	27	0	0	0	0	0	28.9	0.39	0.82	610	6.8
28	28	0	0	0	0	0	29.4	0.4	0.85	690	6.7
29	29	0	0	0	0	-2	22	0.52	1.8	480	2.24
30	30	0	0	0	0	2	30	0.38	1.9	400	6.6

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Std Order	Run Order	Engine load	Gen. Speed	Ignition Timing	AFR	CR	BTE	SFC	CO Emission	NOx Emission	Power Output
31	31	0	-2	0	0	0	29.4	0.4	0.94	870	2.24
32	32	2	0	0	0	0	30.7	0.35	0.7	990	11.8
33	33	0	2	0	0	0	27	0.42	0.95	570	6.6

3.3 Procedure for Data Collection

The experimental procedure was designed to ensure repeatability, accuracy, and reliability of the measurements for the dual-fuel power generation system. The step-by-step procedure is as follows:

1. Engine Preparation and Warm-Up

The FIRMAN 6000 series engine was inspected and lubricated before testing. The engine was started using petrol and allowed to warm up for 15 minutes to reach steady-state operating temperature.

2. Fuel Switching and System Stabilization:

For LPG operation, the Sequential Vapour Phase Injection (SVPI) system was activated. The engine was stabilized at each set of operating conditions (load, speed, ignition timing, air-fuel ratio, compression ratio) for 5-10 minutes before measurements were recorded to ensure consistent performance.

For each of the 33 experimental runs per fuel, the following parameters were measured engine torque, speed, fuel flow rates, exhaust gas temperatures, and emissions (CO and NOx) All measurements were recorded using calibrated sensors connected to the DAQ system. Each run was repeated three times, and average values were calculated to minimize random errors and improve reliability.

Model Development and Data Analysis

Development of Mathematical Models

The experimental data collected from the 33 runs per fuel were used to develop first-order (linear) and secondorder (quadratic) regression models for each response variable (BTE, SFC. CO, NOx, and Power Output) The quadratic models account for linear effects, interaction effects, and curvature, enabling accurate prediction of system behavior within the studied factor ranges.

Analysis of Variance (ANOVA)

ANOVA was performed using Minitab software to evaluate the statistical significance of the developed models and individual model terms. Factors and interactions with p-values <0.05 were considered significant at a 95% confidence level ANOVA results helped identify the most influential factors affecting each performance and emission response.

Model Validation

The adequacy of each model was verified using the Coefficient of Determination (R) and the Adjusted R^{32} (Radj). Residual plots were examined to check for normality, independence, and constant variance, ensuring the models accurately represent the experimental data.

Optimization Technique

The Desirability Function Approach was employed to optimize the dual-fuel engine performance. Using the Response Optimizer tool in Minitab, the multiple response variables were combined into a single composite desirability function (range 0-1).

4.0 Results and Discussions

Development and Analysis of Empirical Models for Petrol Mode

Model Development and Statistical Significance

Based on the experimental data collected, first-order (linear) and second-order (quadratic) empirical models were developed to predict the system's performance and emissions. The equations for the linear models are as follows:

Linear Model Development

$$\textit{Brake Thermal Efficiency} = 5.45 + 0.0820X_1 + 0.00175\,X_2 + 0.0625\,X_3 + 0.433\,X_4 + 0.450\,X_5 \quad (3)$$

$$\textit{Specific Fuel Consumption} = 0.792 - 0.001927\,X_1 - 0.000029\,X_2 - 0.001000\,X_3 - 0.00667\,X_4 - 0.00583\,X_5 \quad (4)$$

$$\textit{CO Emission} = 5.93 - 0.00966\,X_1 - 0.000363\,X_2 - 0.00667\,X_3 - 0.1750\,X_4 - 0.0542\,X_5 \quad (5)$$

$$\textit{NOx Emission} = -660 + 3.811\,X_1 + 0.0833\,X_2 + 3.75\,X_3 + 42.92\,X_4 + 11.7\,X_5 \quad (6)$$

$$\textit{Power Output} = -1.98 + 0.10369\,X_1 + 0.000563\,X_2 + 0.0029\,X_3 + 0.0104\,X_4 + 0.046\,X_5 \quad (7)$$

The statistical significance of these models was evaluated using Analysis of Variance (ANOVA). The ANOVA results for the linear models (Tables 6-10) confirm that the developed models are highly significant, with pvalues < 0.0001 for the overall model in each case.

Table 6: Analysis of Variance for Brake Thermal Efficiency

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	260.929	52.186	15.17	0.000
Linear	5	260.929	52.186	15.17	0.000
Engine Load	1	225.728	225.728	65.61	0.000
Generator Speed	1	2.940	2.940	0.85	0.363
Ignition Timing	1	9.375	9.375	2.72	0.110
Air-Fuel Ratio	1	18.027	18.027	5.24	0.030
Compression Ratio	1	4.860	4.860	1.41	0.245
Error	27	92.891	3.440		
Lack-of-Fit	21	92.876	4.423	1857.53	0.000
Pure Error	6	0.014	0.002		
Total	32	353.820			

Table 7: Analysis of Variance for Specific Fuel Consumption

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.132844	0.026569	30.73	0.000
Linear	5	0.132844	0.026569	30.73	0.000
Engine Load	1	0.124544	0.124544	144.05	0.000
Generator Speed	1	0.000817	0.000817	0.94	0.340
Ignition Timing	1	0.002400	0.002400	2.78	0.107
Air-Fuel Ratio	1	0.004267	0.004267	4.93	0.035
Compression Ratio	1	0.000817	0.000817	0.94	0.340
Error	27	0.023344	0.000865	*	*
Lack-of-Fit	21	0.023344	0.001112		
Pure Error	6	0.000000	0.000000		
Total	32	0.156188			

Table 8: Analysis of Variance for CO Emission

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	6.37719	1.27544	13.36	0.000
Linear	5	6.37719	1.27544	13.36	0.000
Engine Load	1	3.13395	3.13395	32.82	0.000
Generator Speed	1	0.12615	0.12615	1.32	0.261
Ignition Timing	1	0.10667	0.10667	1.12	0.300
Air-Fuel Ratio	1	2.94000	2.94000	30.78	0.000
Compression Ratio	1	0.07042	0.07042	0.74	0.398
Error	27	2.57855	0.09550	*	*
Lack-of-Fit	21	2.57855	0.12279		
Pure Error	6	0.00000	0.00000		
Total	32	8.95573			

Table 9: Analysis of Variance for NOx Emission

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	707807	141561	44.69	0.000
Linear	5	707807	141561	44.69	0.000
Engine Load	1	487307	487307	153.84	0.000
Generator Speed	1	6667	6667	2.10	0.158
Ignition Timing	1	33750	33750	10.65	0.003
Air-Fuel Ratio	1	176817	176817	55.82	0.000
Compression Ratio	1	3267	3267	1.03	0.319

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Error	27	85526	3168	*	*
Lack-of-Fit	21	85526	4073		
Pure Error	6	0	0		
Total	32	793333			

Table 10: Analysis of Variance for Power Output

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	361.143	72.229	162.67	0.000
Linear	5	361.143	72.229	162.67	0.000
Engine Load	1	360.758	360.758	812.47	0.000
Generator Speed	1	0.304	0.304	0.68	0.415
Ignition Timing	1	0.020	0.020	0.05	0.832
Air-Fuel Ratio	1	0.010	0.010	0.02	0.879
Compression Ratio	1	0.050	0.050	0.11	0.739
Error	27	11.989	0.444	*	*
Lack-of-Fit	21	11.989	0.571		
Pure Error	6	0.000	0.000		
Total	32	373.132			

The statistical significance of the developed first-order linear models for the petrol mode was rigorously assessed using Analysis of Variance (ANOVA), as presented in Tables 6 to 10 for Brake Thermal Efficiency, Specific Fuel Consumption, CO Emission, NOx Emission, and Power Output, respectively. These tables collectively confirm that the empirical models are highly significant, with exceptionally low p-values ($p < 0.0001$) for the overall model in each case. Furthermore, the ANOVA results identify the individual influence of each factor; Engine Load consistently emerges as the most statistically significant parameter across all responses, while factors like Generator Speed often show a lesser impact. This analysis validates the use of these linear equations for initial prediction and clearly establishes a hierarchy of parameter influence on the generator's performance and emissions.

4.1.2 Model Adequacy Checking

The goodness-of-fit for the linear models is summarized in Table 11. The high R-squared (R-sq) and adjusted R-squared (R-sq(adj)) values indicate that the models explain a large portion of the variability in the data.

Table 11: Coefficients of determination and error standard deviation for the first order models

Responses	S	R-sq	R-sq(adj)
BTE	1.85483	73.75%	68.88%
SFC	0.0294038	85.05%	82.29%
COE	0.309034	71.21%	65.88%
NOxE	56.2818	89.22%	87.22%
PO	0.666354	96.79%	96.19%

To further validate the models, the residual plots were analyzed. The residual plots for Brake Thermal Efficiency, Specific Fuel Consumption, CO Emission, NOx Emission, and Power Output (Tables 6 to 10) show a random scatter of residuals, confirming that the assumptions of constant variance and normality are satisfied, and thus the models are adequate.

Residual plots for power output

Enhanced Modelling with Quadratic Models and Optimization

To capture the non-linear relationships and interaction effects between factors, more robust quadratic models were developed.

Quadratic Model Development

$$\textbf{Brake Thermal Efficiency} = -107.9 + 0.1556 X_1 + 0.0357 X_2 + 0.620 X_3 + 6.18 X_4 + 3.69 X_5 - 0.001084 X_1^2 - 0.000003 X_2^2 - 0.00494 X_3^2 - 0.1203 X_4^2 - 0.144 X_5^2 - 0.000009 X_1X_2 + 0.001656 X_1X_3 - 0.00047 X_1X_4 + 0.00687 X_1X_5 + 0.000019 X_2X_3 - 0.000906 X_2X_4 - 0.00037 X_2X_5 - 0.0100 X_3X_4 - 0.0362 X_3X_5 + 0.069 X_4X_5 \quad (8)$$

Specific Fuel Consumption = $2.108 - 0.00326 X_1 - 0.000427 X_2 - 0.01079 X_3 - 0.0876 X_4 - 0.0080 X_5 + 0.000019 X_1^2 + 0.000000 X_2^2 + 0.000032 X_3^2 + 0.001428 X_4^2 - 0.00054 X_5^2 - 0.000028 X_1X_3 - 0.000016 X_1X_4 - 0.000031 X_1X_5 + 0.000001 X_2X_3 + 0.000016 X_2X_4 + 0.000006 X_2X_5 + 0.000250 X_3X_4 + 0.000500 X_3X_5 - 0.00125 X_4X_5$ (9)

CO Emission = $34.0 - 0.0030 X_1 - 0.00829 X_2 - 0.2013 X_3 - 1.357 X_4 - 1.378 X_5 + 0.000162 X_1^2 + 0.000001 X_2^2 + 0.000420 X_3^2 + 0.03238 X_4^2 + 0.0345 X_5^2 - 0.000004 X_1X_2 - 0.000144 X_1X_3 + 0.000156 X_1X_4 - 0.001531 X_1X_5 + 0.000024 X_2X_3 + 0.000053 X_2X_4 + 0.000225 X_2X_5 + 0.00450 X_3X_4 + 0.00513 X_3X_5 - 0.0006 X_4X_5$ (10)

The ANOVA for these quadratic models (Tables 12 - 16) shows an even better fit, with significant quadratic and interaction terms. The coefficients of determination for the quadratic models are exceptionally high (all above 96.5%), making them ideal for optimization.

Table 12: Analysis of Variance for Brake Thermal Efficiency

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	20	345.916	17.2958	26.26	0.000
Linear	5	91.120	18.2240	27.67	0.000
Engine Load	1	54.881	54.8808	83.32	0.000
Generator Speed	1	1.705	1.7045	2.59	0.134
Ignition Timing	1	15.961	15.9607	24.23	0.000
Air-Fuel Ratio	1	12.549	12.5492	19.05	0.001
Compression Ratio	1	6.025	6.0245	9.15	0.011
Square	5	71.382	14.2764	21.68	0.000
Engine Load*Engine Load	1	52.836	52.8364	80.22	0.000
Generator Speed*Generator Speed	1	0.426	0.4263	0.65	0.437
Ignition Timing*Ignition Timing	1	7.367	7.3668	11.18	0.006
Air-Fuel Ratio*Air-Fuel Ratio	1	6.999	6.9986	10.63	0.007
Compression Ratio*Compression Ratio	1	0.625	0.6247	0.95	0.349
2-Way Interaction	10	13.605	1.3605	2.07	0.117
Engine Load*Generator Speed	1	0.090	0.0900	0.14	0.718
Engine Load*Ignition Timing	1	7.022	7.0225	10.66	0.007
Engine Load*Air-Fuel Ratio	1	0.022	0.0225	0.03	0.856
Engine Load*Compression Ratio	1	1.210	1.2100	1.84	0.200
Generator Speed*Ignition Timing	1	0.022	0.0225	0.03	0.856
Generator Speed*Air-Fuel Ratio	1	2.103	2.1025	3.19	0.099
Generator Speed*Compression Ratio	1	0.090	0.0900	0.14	0.718
Ignition Timing*Air-Fuel Ratio	1	0.640	0.6400	0.97	0.344
Ignition Timing*Compression Ratio	1	2.102	2.1025	3.19	0.099
Air-Fuel Ratio*Compression Ratio	1	0.302	0.3025	0.46	0.511
Error	12	7.904	0.6587	-	-
Lack-of-Fit	6	7.890	1.3149	552.27	0.000
Pure Error	6	0.014	0.0024	-	-
Total	32	353.820	-	-	-

Table 13: Analysis of Variance for Specific Fuel Consumption

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	20	0.155049	0.007752	81.69	0.000
Linear	5	0.049752	0.009950	104.86	0.000
Engine Load	1	0.040768	0.040768	429.61	0.000
Generator Speed	1	0.000594	0.000594	6.26	0.028
Ignition Timing	1	0.004261	0.004261	44.91	0.000
Air-Fuel Ratio	1	0.003401	0.003401	35.84	0.000

Compression Ratio	1	0.000728	0.000728	7.67	0.017
Square	5	0.018555	0.003711	39.11	0.000
Engine Load*Engine Load	1	0.016616	0.016616	175.10	0.000
Generator Speed*Generator Speed	1	0.000015	0.000015	0.16	0.695
Ignition Timing*Ignition Timing	1	0.000312	0.000312	3.29	0.095
Air-Fuel Ratio*Air-Fuel Ratio	1	0.000986	0.000986	10.39	0.007
Compression Ratio*Compression Ratio	1	0.000009	0.000009	0.09	0.767
2-Way Interaction	10	0.003650	0.000365	3.85	0.015
Engine Load*Generator Speed	1	0.000000	0.000000	0.00	1.000
Engine Load*Ignition Timing	1	0.002025	0.002025	21.34	0.001
Engine Load*Air-Fuel Ratio	1	0.000025	0.000025	0.26	0.617
Engine Load*Compression Ratio	1	0.000025	0.000025	0.26	0.617
Generator Speed*Ignition Timing	1	0.000025	0.000025	0.26	0.617
Generator Speed*Air-Fuel Ratio	1	0.000625	0.000625	6.59	0.025
Generator Speed*Compression Ratio	1	0.000025	0.000025	0.26	0.617
Ignition Timing*Air-Fuel Ratio	1	0.000400	0.000400	4.22	0.063
Ignition Timing*Compression Ratio	1	0.000400	0.000400	4.22	0.063
Air-Fuel Ratio*Compression Ratio	1	0.000100	0.000100	1.05	0.325
Error	12	0.001139	0.000095	-	-
Lack-of-Fit	6	0.001139	0.000190	*	*
Pure Error	6	0.000000	0.000000	-	-
Total	32	0.156188	-	-	-

Table 14: Analysis of Variance for CO Emission

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	20	8.65013	0.43251	16.98	0.000
Linear	5	3.00623	0.60125	23.61	0.000
Engine Load	1	0.51991	0.51991	20.41	0.001
Generator Speed	1	0.13943	0.13943	5.47	0.037
Ignition Timing	1	0.15891	0.15891	6.24	0.028
Air-Fuel Ratio	1	2.06250	2.06250	80.99	0.000
Compression Ratio	1	0.12549	0.12549	4.93	0.046
Square	5	1.88999	0.37800	14.84	0.000
Engine Load*Engine Load	1	1.18291	1.18291	46.45	0.000
Generator Speed*Generator Speed	1	0.03102	0.03102	1.22	0.291
Ignition Timing*Ignition Timing	1	0.05340	0.05340	2.10	0.173
Air-Fuel Ratio*Air-Fuel Ratio	1	0.50699	0.50699	19.91	0.001
Compression Ratio*Compression Ratio	1	0.03604	0.03604	1.42	0.257
2-Way Interaction	10	0.38295	0.03830	1.50	0.249
Engine Load*Generator Speed	1	0.01823	0.01823	0.72	0.414
Engine Load*Ignition Timing	1	0.05290	0.05290	2.08	0.175
Engine Load*Air-Fuel Ratio	1	0.00250	0.00250	0.10	0.759
Engine Load*Compression Ratio	1	0.06003	0.06003	2.36	0.151
Generator Speed*Ignition Timing	1	0.03803	0.03803	1.49	0.245
Generator Speed*Air-Fuel Ratio	1	0.00722	0.00722	0.28	0.604
Generator Speed*Compression Ratio	1	0.03240	0.03240	1.27	0.281
Ignition Timing*Air-Fuel Ratio	1	0.12960	0.12960	5.09	0.044
Ignition Timing*Compression Ratio	1	0.04202	0.04202	1.65	0.223
Air-Fuel Ratio*Compression Ratio	1	0.00003	0.00003	0.00	0.976
Error	12	0.30561	0.02547	-	-
Lack-of-Fit	6	0.30561	0.05093	*	*
Pure Error	6	0.00000	0.00000	-	-
Total	32	8.95573	-	-	-

The Analysis of Variance (ANOVA) for the second-order quadratic models, detailed in Tables 12 through 16 for Brake Thermal Efficiency, Specific Fuel Consumption, CO Emission, NOx Emission, and Power Output

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respectively, demonstrates a superior model fit compared to the linear models. These tables reveal that the "Square" terms are collectively highly significant ($p < 0.0001$ for most responses), confirming the presence of curvature in the system's behavior that the first-order models could not capture. Furthermore, specific twoway interactions, such as between Engine Load and Ignition Timing, also emerge as statistically significant.

5.0 Conclusion and Recommendation

5.1 Conclusion

This study successfully achieved its aim through the rigorous application of Response Surface Methodology (RSM) with a Central Composite Design (CCD), leading to the development of highly accurate, validated empirical models for a petrol-LP-G dual-fuel generator The second-order polynomial models created for both fuel modes exhibited exceptional predictive power, with coefficients of determination (R) consistently exceeding 96 5%, a claim robustly supported by significant ANOVA results (p-value < 0.0001). The subsequent multi-response optimization, employing the Desirability Function approach, yielded distinct and scientificallyderived optimal calibrations for each fuel. A critical comparative analysis of these optima revealed a definitive performance-emission trade-off The LPG system demonstrated a remarkable capacity for power, yielding a 22. 9% increase in Power Output while maintaining a Brake Thermal Efficiency virtually identical (-31.7%) to petrol. However, this high-power optimization strategy for LPG came with notable compromises a 5 56% higher mass-based Specific Fuel Consumption, due to its lower volumetric efficiency, and significantly elevated emissions, with Carbon Monoxide (CO) and Nitrogen Oxides (NOx) rising by 66.2% and 14.1%, respectively.

These findings quantitatively underscore that LPG is a superior fuel for power density but decisively challenge its blanket classification as a "cleaner" alternative, highlighting that emission outcomes are intrinsically tied to calibration priorities. The research proves that the common practice of using petrol-optimized maps for LPG operation is fundamentally flawed and leads to suboptimal performance The high fidelity of the developed models means the can be used not just for optimization, but also for sensitivity analysis to understand the system behavior under off-design conditions.

5.2 Recommendations

This section provides targeted, stakeholder-specific recommendations to improve the performance, efficiency, and environmental compliance of dual-fuel (petrol-LPG) generator systems based on the study's findings

1. LPG offers significant performance benefits, but users must base fuel choice on cost per kWh and ensure fuel-specific calibration.
2. Users should be mindful of emission regulations, especially due to the rise in NOx when using LPG.
3. Engineers must replace generic tuning with dedicated ECU maps and optimized ignition/air-fuel strategies for each fuel
4. Manufacturers should integrate adaptive control systems and key sensors to maintain optimal, closedloop engine operation.
5. Researchers and policymakers should expand studies to broader emissions and operation modes, and enforce standards ensuring proper calibration for dual-fuel systems.

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