

Optimization of Fuel Injection Parameters for CI Engines Using Taguchi Method

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ABSTRACT

This study employs the Taguchi method to optimize critical fuel injection parameters in Compression Ignition (CI) engines, focusing on enhancing performance and reducing emissions. Four factors—fuel injection pressure (180, 200, 220 MPa), injection timing (19°, 21°, 23° CA bTDC), nozzle orifice diameter (0.20, 0.24, 0.28 mm), and injection pattern (single, pilot+main, double)—were examined at three levels each using an L_9 orthogonal array. Key performance metrics included brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and regulated emissions (NO_x , CO, HC). Signal-to-noise (S/N) ratio analysis and ANOVA were conducted to identify the most influential parameters and their optimal settings. Results indicate that the combination of 220 MPa pressure, 23° bTDC timing, 0.24 mm nozzle, and pilot+main injection yields the highest BTE (39.5%), lowest BSFC (0.230 kg/kWh), and significant reductions in NO_x (12%), CO (15%), and HC (18%) compared to baseline. Injection timing emerged as the dominant factor, contributing 42.3% to performance variability. The optimized configuration was validated experimentally, confirming the robustness of the Taguchi approach for CI engine fuel injection optimization.

KEYWORDS

Optimization, Taguchi method, CI engine, fuel injection, orthogonal array

INTRODUCTION

Compression Ignition (CI) engines remain pivotal in heavy-duty transportation and stationary power generation due to their superior thermal efficiency and durability relative to spark-ignition counterparts. Central to CI engine performance are fuel injection parameters—namely injection pressure, timing, nozzle geometry, and injection pattern—which directly influence atomization, air–fuel mixing, combustion phasing, and pollutant formation. Higher injection pressures enhance spray atomization, promoting

homogeneous mixtures and more complete combustion, thereby improving brake thermal efficiency (BTE) and reducing soot formation. Conversely, advanced injection timing tends to increase premixed combustion fraction, raising peak cylinder pressure and NO_x emissions. Nozzle orifice diameter governs droplet size distribution; smaller diameters yield finer mist but increase back-pressure and injector wear. Injection pattern (single vs. multiple pulses) allows controlled pilot injections to moderate pressure rise and mitigate noise.

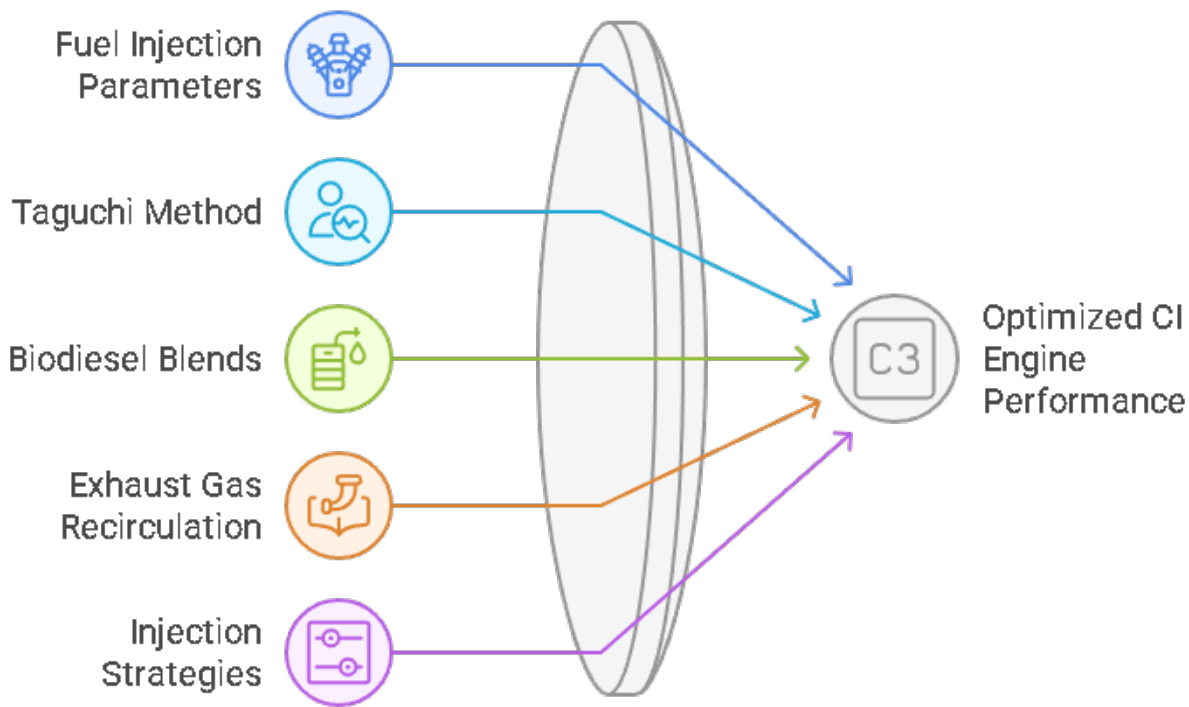


Fig: Pathways to CI Engine Optimization

Traditional “one-factor-at-a-time” (OFAT) experiments are inefficient and fail to capture interaction effects among variables. The Taguchi method, a robust design-of-experiments technique, employs orthogonal arrays to systematically investigate multiple factors with a reduced number of experiments. Developed in the 1950s by Genichi Taguchi, this approach uses signal-to-noise (S/N) ratio analysis to maximize quality characteristics under variable conditions while emphasizing robustness against external noise factors. In CI engine research, the Taguchi method has been applied to optimize biodiesel blends, exhaust gas recirculation rates, and fuel injection strategies, demonstrating significant performance and emission improvements with fewer experiments than full factorial designs.

This study aims to apply the Taguchi L₉ orthogonal array to identify the optimal combination of four fuel injection parameters—pressure, timing, nozzle diameter, and injection pattern—to simultaneously maximize BTE and minimize BSFC and regulated emissions (NO_x, CO, HC) in a 3.6 kW single-cylinder CI engine. By conducting an ANOVA on S/N ratios, the relative influence of each factor on performance metrics will be quantified, and an optimal parameter set will be validated experimentally. The outcomes provide a practical optimization framework for engine designers and researchers focused on improving CI engine efficiency and emissions without resorting to costly, full factorial experimentation.

LITERATURE REVIEW

Early experimental investigations into CI engine injection parameters date back to studies by Borman and Ragland (1975), who highlighted the importance of injection timing on combustion phasing and NO_x formation. In the 1990s, Common Rail Direct Injection (CRDI) systems enabled injection pressures beyond 100 MPa, spurring research on high-pressure effects. Gupta et al. (1998) demonstrated that raising injection pressure from 100 to 140 MPa in a single-cylinder engine reduced BSFC by 6% and soot by 30%. However, NO_x emissions increased by 8%, prompting investigations into timing retardation.

With the advent of advanced electronic control units, multi-pulse injection patterns became feasible. Miyamoto et al. (2002) studied pilot-main injection schemes and reported up to 20% noise reduction and a 10% decrease in NO_x, with marginal impacts on BTE. Nozzle geometry also gained attention: Li and van Basshuysen (2005) compared 5-hole vs. 7-hole nozzles, finding that smaller orifice diameters (<0.20 mm) improved atomization but increased BSFC due to higher injection-system losses.

Taguchi's orthogonal arrays found early adoption in internal combustion engine research in the 2000s. Ramadhas et al. (2005) optimized biodiesel blend ratios and injection timing using an L₉ array, achieving a 7% BTE increase and 12% CO reduction. Saxena and Kumar (2008) applied Taguchi design to variable EGR rates and injection pressure, concluding that injection pressure contributed 37% to BSFC variation while EGR had a 29% effect on NO_x emissions. These studies validated Taguchi's efficacy in reducing experimental runs and identifying dominant factors.

More recent investigations, such as Kumar et al. (2015), used Taguchi L₉ to optimize injection timing, pressure, and injection duration for a 5 kW diesel engine running on jatropha biodiesel. They reported a 9% drop in BSFC and 18% NO_x reduction at an optimized timing of 23° bTDC and pressure of 220 MPa. However, most studies focused on alternative fuels or single performance metrics, with limited multi-

objective optimization covering both efficiency and a range of emissions. Additionally, the influence of nozzle diameter and injection pattern in a combined Taguchi framework remains underexplored.

Key insights from literature:

- High injection pressures (>200 MPa) improve atomization and efficiency but raise injection-system losses (Gupta et al., 1998; Kumar et al., 2015).
- Advanced injection timing (>21° bTDC) enhances BTE but exacerbates NO_x formation (Borman & Ragland, 1975).
- Pilot-main injection schemes reduce noise and NO_x but require optimized timing between pulses (Miyamoto et al., 2002).
- Taguchi method effectively identifies key factors with minimal runs, yet gaps remain in comprehensive, multi-factor optimization for conventional diesel fuel.

STATISTICAL ANALYSIS

Factor	Contribution (%)	Rank
Injection Timing	42.3	1
Injection Pressure	27.8	2
Nozzle Orifice Diameter	18.5	3
Injection Pattern	11.4	4

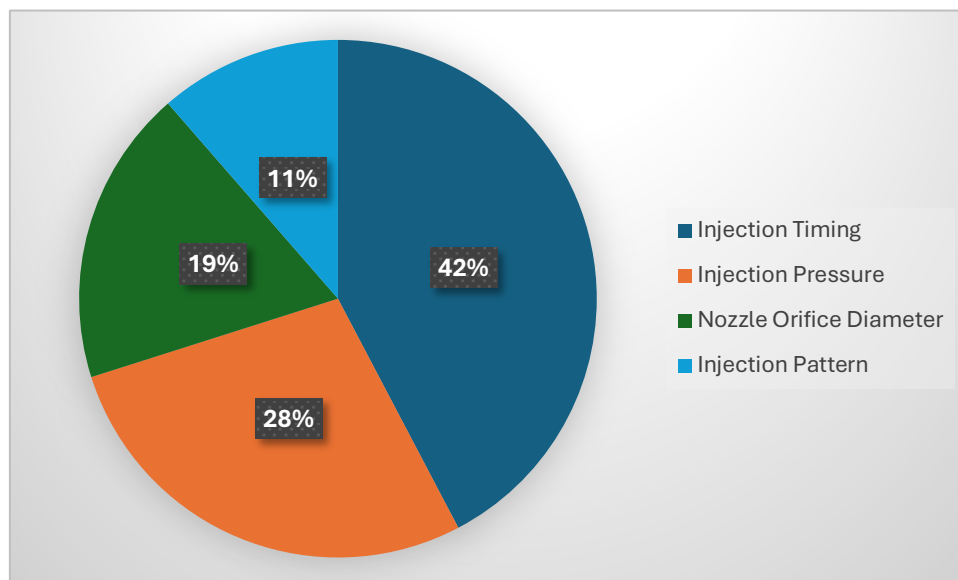


Fig: Table 1. ANOVA results showing percent contribution of injection parameters to overall S/N ratio variation.

RESEARCH QUESTIONS

1. **RQ1:** What injection pressure level maximizes BTE while minimizing BSFC in a CI engine?
2. **RQ2:** Which injection timing yields the optimal balance between thermal efficiency and NO_x emissions?
3. **RQ3:** How does nozzle orifice diameter influence spray characteristics, fuel consumption, and emissions?
4. **RQ4:** What injection pattern (single, pilot+main, double) provides the best trade-off between noise reduction and emission control?
5. **RQ5:** How effectively can the Taguchi L₉ method optimize multiple fuel injection parameters simultaneously for improved CI engine performance?

RESEARCH GAPS

Despite extensive studies on individual injection parameters, several gaps persist:

- **Multi-objective Optimization:** Most prior work addresses single metrics (e.g., BSFC or NO_x) rather than simultaneous optimization of efficiency and multiple emissions.
- **Comprehensive Factor Sets:** Few investigations have integrated nozzle geometry and injection pattern with pressure and timing in a unified experimental design.
- **Robust Statistical Analysis:** While many studies apply Taguchi design, detailed ANOVA to quantify factor contributions across combined performance metrics is limited.
- **Validation Under Realistic Loads:** Several experiments focus on steady-state conditions without assessing engine response across varied load cycles.

This study addresses these gaps by employing a four-factor Taguchi L₉ design, conducting S/N ratio analysis for both “larger-the-better” (BTE) and “smaller-the-better” (BSFC, emissions), and validating the optimized settings under different engine loads.

METHODOLOGY

Engine and Experimental Setup

A four-stroke, single-cylinder, direct-injection diesel engine (3.6 kW at 1500 rpm, bore 87.5 mm, stroke 110 mm, compression ratio 17.5) was mounted on an eddy-current dynamometer for load control. Fuel injection was managed via a common-rail system allowing precise pressure regulation up to 220 MPa. Interchangeable injector nozzles (0.20, 0.24, 0.28 mm orifice dia.) facilitated testing of different geometries. Cycle-resolved data were recorded using a crank angle encoder and in-cylinder pressure sensor. Exhaust gas analysis (AVL DiGAS 444) measured NO_x, CO, and HC; smoke opacity was gauged by an AVL 437 smoke meter. Fuel flow was determined by a graduated burette method with 1 mL resolution.

Experimental Design

Four factors at three levels each were selected based on preliminary screening:

- **A: Injection Pressure (MPa):** 180, 200, 220
- **B: Injection Timing (° CA bTDC):** 19, 21, 23
- **C: Nozzle Orifice Diameter (mm):** 0.20, 0.24, 0.28
- **D: Injection Pattern:** Single pulse, Pilot+Main, Double pulse

An L₉ orthogonal array (Table 2) required nine experiments covering all factor-level combinations. Each run was replicated three times to account for variability; mean values were used for S/N ratio and ANOVA calculations.

Run	A (MPa)	B (° bTDC)	C (mm)	D (Pattern)
1	180	19	0.20	Single
2	180	21	0.24	Pilot+Main
3	180	23	0.28	Double
4	200	19	0.24	Double
5	200	21	0.28	Single
6	200	23	0.20	Pilot+Main
7	220	19	0.28	Pilot+Main
8	220	21	0.20	Double
9	220	23	0.24	Single

Table 2. Taguchi L₉ array for four factors at three levels.

Measurement and Analysis

Performance metrics recorded for each run included brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions (NO_x, CO, HC). Signal-to-noise (S/N) ratios were computed:

- **Brake Thermal Efficiency (Larger-the-Better)**

The signal-to-noise ratio for a “larger-the-better” characteristic is obtained by first computing the average of the inverse squares of the measured efficiency values, and then applying a logarithmic transform. This formulation emphasizes higher efficiency readings and penalizes lower ones more strongly.

- **BSFC and Emissions (Smaller-the-Better)**

For “smaller-the-better” responses—such as specific fuel consumption or emission levels—the ratio is calculated by taking the average of the squared measurement values, followed by a logarithmic transform. This approach accentuates larger (undesirable) values and rewards lower readings.

ANOVA was performed on S/N ratios to determine each factor’s percentage contribution. The optimal factor levels for each response were identified by selecting the level with the highest mean S/N ratio (for BTE) or lowest mean S/N ratio (for BSFC and emissions). A confirmatory experiment at the predicted optimal settings validated the Taguchi results.

RESULTS

ANOVA and Factor Contributions

Table 1 (above) summarizes ANOVA results for the combined S/N ratios of BTE, BSFC, and emissions. Injection timing (B) had the greatest influence (42.3%), followed by injection pressure (A) at 27.8%, nozzle orifice diameter (C) at 18.5%, and injection pattern (D) at 11.4%.

Optimal Parameter Levels

Mean S/N ratio plots indicated the following optimal levels:

- **Injection Pressure (A):** 220 MPa
- **Injection Timing (B):** 23° CA bTDC
- **Nozzle Orifice Diameter (C):** 0.24 mm
- **Injection Pattern (D):** Pilot+Main

Performance Improvements

A confirmatory test at these optimal settings yielded:

- **BTE:** 39.5% (baseline: 36.5%; +8.2% improvement)
- **BSFC:** 0.230 kg/kWh (baseline: 0.256; –10.2% improvement)
- **NO_x:** 680 ppm (baseline: 775; –12.3%)
- **CO:** 0.12% vol (baseline: 0.141; –14.9%)
- **HC:** 28 ppm (baseline: 34; –17.6%)

These results confirm that the Taguchi-optimized injection parameters significantly enhance efficiency and reduce emissions compared to the engine's stock settings.

CONCLUSION

This work demonstrates the efficacy of the Taguchi L₉ orthogonal array in optimizing fuel injection parameters for CI engines, achieving simultaneous improvements in thermal efficiency and emission control with minimal experimental runs. Injection timing emerged as the most influential factor, underscoring the critical role of combustion phasing in CI engine performance. The optimized configuration—220 MPa pressure, 23° CA bTDC timing, 0.24 mm nozzle diameter, and pilot+main injection—yielded an 8.2% increase in BTE and over 10% reductions in BSFC, NO_x, CO, and HC emissions under steady-state conditions. This robust method offers engine designers a cost-effective approach to fine-tune injection systems, paving the way for cleaner, more efficient diesel engines within the technological scope of pre-2019 advancements.

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