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“Impact of Compression Ratio on the Performance of CNG Engines”

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ABSTRACT:

Compression ratio in engines refers to the ratio of the total cylinder volume when the piston is at the bottom of its stroke (known as the "bottom dead center" or BDC) to the total cylinder volume when the piston is at the top of its stroke (known as the "top dead center" or TDC). In other words, it is the ratio of the maximum to the minimum volume within a cylinder during the engine's operation. Compression ratios of 10, 11, 11.5, 12, 12.5 & 13 and engine speeds of 1000 to 5000 rpm, in increments of 100 rpm, were utilized. In the present study, the effect of different compression ratios was studied and optimum compression ratio was established for a dedicated CNG engine. The results show that with the increase in compression ratio, the performance characteristics viz. power, torque, brake thermal efficiency and brake specific fuel consumption are improved. The CNG engine has established itself as a viable alternative to diesel engines in both heavy commercial and passenger transport applications. The expansion of CNG distribution networks and the implementation of strict emission regulations have prompted Original Equipment Manufacturers (OEMs) to focus on the development of CNG vehicles across various market segments. As the global automotive industry continues its relentless pursuit of sustainable and environmentally friendly transportation solutions, compressed natural gas (CNG) has emerged as a promising alternative to traditional gasoline and diesel fuels. CNG, composed mainly of methane, offers several advantages, including lower greenhouse gas emissions and reduced reliance on fossil fuels. In this context, dedicated CNG engines have gained significant attention as they are purpose-built to maximize the potential benefits of this alternative fuel source. Among the myriad factors that influence the performance of CNG engines, the compression ratio stands out as a pivotal parameter deserving comprehensive investigation.

The compression ratio, defined as the ratio of the cylinder's maximum and minimum volumes, plays a fundamental role in determining an engine's efficiency, power output, and emissions characteristics. It is a parameter of paramount importance in internal combustion engines, irrespective of the fuel type. However, its influence on dedicated CNG engines, specifically tailored to harness the unique properties of natural gas, has not been explored in depth. Understanding the intricate relationship between compression ratio and CNG engine performance is essential for optimizing engine design and achieving the desired balance between efficiency, power, and emissions.

Keywords: CNG engine, Thermal Efficiency, Compression Ratio, emission control, CO-NO_x-THC-CH₄ emissions, ECU calibration.

I. INTRODUCTION.

1.1 Worldwide Scenario

Natural Gas Vehicles (NGVs), mainly using Compressed Natural Gas (CNG), are widely adopted in countries such as China, Iran, India, Pakistan, and Argentina. Due to lower emissions and cost advantages, CNG has become an important alternative fuel for both passenger and commercial transport, increasing the need for engine optimization research. Compression Ratio (CR) is a key parameter influencing CNG engine performance. Because CNG has a high octane number and strong knock resistance, higher compression ratios can be safely used compared to gasoline engines. Increasing CR improves thermal efficiency and reduces Brake Specific Fuel Consumption (BSFC), resulting in better engine performance and fuel economy. Experimental studies show that increasing CR improves power, torque, and Brake Thermal Efficiency (BTE) up to an optimum range, typically between 9:1 and 16:1 depending on engine design and operating conditions. Beyond this limit, performance gains reduce due to knocking and mechanical limitations. From an emissions perspective, higher CR reduces CO and HC emissions due to better combustion, but NO_x emissions may increase because of higher combustion temperatures. To address this, techniques such as Exhaust Gas Recirculation (EGR), lean-burn operation, and Hydrogen-Enriched CNG (HCNG) are used to control emissions while maintaining efficiency. Recent advancements like Direct Injection CNG (DI-CNG) and optimized ignition systems allow engines to operate at higher CRs with improved combustion stability and reduced knocking. However, challenges remain in knock prediction, transient operation, and long-term durability. Overall, optimizing compression ratio is essential for improving efficiency and emissions in CNG engines, making it a key area of research in sustainable engine development.

1.2 Scenario In India

India has experienced substantial growth in the adoption of CNG vehicles over the past decade. As of early 2025, the number of CNG vehicles in the country is expected to reach nearly 7.5 million, compared to approximately 2.6 million in FY2016, representing a Compound Annual Growth Rate (CAGR) of nearly 12%. The sales of CNG-powered vehicles, including passenger cars, SUVs, buses, taxis, three-wheelers, and commercial vehicles, have increased considerably due to rising fuel costs and stricter emission norms. The market share of CNG vehicles in the passenger vehicle segment has also increased significantly in recent years. Simultaneously, the number of CNG filling stations across India has expanded rapidly, improving accessibility and supporting wider adoption. Indian operating conditions such as high ambient temperatures, stop-and-go urban traffic, varying fuel quality, and hilly terrains make engine optimization highly important. Most existing Indian CNG vehicles are either converted gasoline engines or dual-fuel systems, where the compression ratio is not fully optimized for dedicated CNG operation. This creates a significant opportunity for research on dedicated high-compression CNG engines.

Gaps and Opportunities in the Indian Context

- Limited Indian-specific studies are available on the influence of compression ratio on CNG engine performance and emissions under local operating conditions.
- Variations in Indian CNG fuel composition may influence optimum CR and knocking characteristics.
- More research is needed on transient and part-load operating conditions that represent real Indian driving cycles.
- Dedicated high-compression CNG engine designs can improve fuel economy, emissions, and overall operational efficiency for Indian transportation systems.

1.3 Scope of the Project

This study investigates the effect of compression ratio on the performance, combustion, and emission characteristics of a CNG-fueled spark ignition engine using experimental and simulation methods. Compression ratio is a key parameter that strongly influences engine efficiency, power output, fuel consumption, and emissions. Since CNG has high knock resistance, higher compression ratios can be used to improve engine performance. In the experimental work, engine tests are conducted at different compression ratios to measure performance parameters such as Brake Thermal Efficiency (BTE), Brake Power (BP), torque, and Brake Specific Fuel Consumption (BSFC). Emissions like CO, HC, NO_x, and CO₂ are also analyzed. A simulation model is developed using tools like MATLAB or GT-Power to study combustion and emission behavior, and results are validated with experimental data. The study aims to identify the optimum compression ratio that provides maximum efficiency with minimum emissions while considering knock limits and practical engine constraints.

1.4 Purpose of the Study

The primary purpose of this study is to analyze and quantify the influence of compression ratio variations on the performance, combustion, and emission characteristics of dedicated CNG engines using both experimental and simulation approaches. With the increasing demand for cleaner and more economical transportation systems, CNG has emerged as a promising alternative fuel due to its lower emissions and better combustion characteristics. Optimizing the compression ratio is essential for improving thermal efficiency, fuel economy, and power output while maintaining acceptable emission levels and engine durability. This study aims to provide valuable insights into the relationship between compression ratio and engine performance. The findings of this research can assist researchers, engine manufacturers, and policymakers in developing advanced, efficient, and environmentally sustainable CNG engine technologies.

II. LITERATURE REVIEW.

2.1 Overview:

2.1.1 Thermodynamic Basis and Effect of Compression Ratio (CR)

Compression Ratio (CR) is an important thermodynamic parameter that directly affects the thermal efficiency of spark-ignition engines. Increasing the CR improves the theoretical Otto-cycle efficiency by increasing pressure and temperature during combustion, resulting in higher work output per cycle. Since CNG possesses a high octane number and strong knock resistance, it can operate safely at higher CRs compared to gasoline engines. Higher CR generally improves Brake Thermal Efficiency (BTE) and reduces Brake Specific Fuel Consumption (BSFC). However, increased combustion temperature at higher CR may lead to higher NO_x emissions.

2.1.2 Experimental Evidence on CR and Performance

Several experimental studies have shown that increasing the compression ratio improves engine performance parameters such as power output, torque, BTE, and fuel economy up to an optimum limit. Studies conducted on CNG engines with CR ranges from 9:1 to 16:1 reported improved thermal efficiency and lower BSFC. However, the optimum CR varies depending on engine geometry, ignition timing, fueling method, and operating conditions.

2.1.3 Emission Characteristics with Increased CR

Higher compression ratios generally improve combustion quality, thereby reducing CO and HC emissions. However, NO_x emissions may increase because of higher in-cylinder temperatures. Researchers have suggested the use of lean-burn operation, Exhaust Gas Recirculation (EGR), and hydrogen enrichment techniques to reduce NO_x emissions while maintaining efficiency improvements.

2.1.4 Role of Fueling Method: Port Injection vs Direct Injection

Direct Injection CNG (DI-CNG) systems improve mixture formation and volumetric efficiency, allowing engines to operate at higher compression ratios with reduced knocking tendency. DI-CNG engines demonstrate better thermal efficiency and lower CO/HC emissions compared to Port Fuel Injection (PFI) systems. However, slight increases in NO_x emissions may occur without suitable emission control techniques.

2.1.5 Modeling and Simulation Studies

Simulation tools such as MATLAB, GT-Power, and CFD models are widely used to study the effects of CR on engine performance, combustion, and emissions. These models help analyze pressure variation, heat release rate, knock tendency, and combustion behavior under different operating conditions. Modeling studies also assist in reducing experimental time and cost.

2.1.6 Alternative Fuel Strategies and HCNG Blends

Hydrogen-enriched CNG (HCNG) blends improve combustion speed and flame propagation characteristics. HCNG operation enhances thermal efficiency and reduces CO and HC emissions while improving combustion stability. However, NO_x emissions may increase due to higher combustion temperatures, which can be controlled using EGR and ignition timing optimization.

2.2 Gaps and Research Opportunities

Despite extensive global research, several challenges and research gaps remain in the optimization of compression ratio for CNG engines:

1. Limited studies are available on transient and part-load operating conditions commonly experienced in urban driving.
2. Comparative studies between Port Injection and Direct Injection systems under identical operating conditions are limited.
3. Knock characteristics at high compression ratios with varying CNG fuel compositions require further investigation.

4. Indian-specific studies considering local fuel quality, climate conditions, and driving patterns are insufficient.
5. Addressing these gaps through experimental analysis and simulation-based studies can provide valuable insights for designing efficient dedicated CNG engines.

2.3 CR Effects on Performance and Emissions in CNG Engines

2.3.1 Exploiting CNG's Knock Resistance

Due to the high octane number of CNG, engines can operate at higher compression ratios than conventional gasoline engines. Increasing CR improves thermal efficiency and reduces BSFC while enhancing engine performance.

2.3.2 Direct Injection (DI-CNG) and Higher CR Operation

DI-CNG systems improve fuel-air mixing and reduce knock tendency, allowing operation at compression ratios above 13:1. These systems provide improved BTE and lower CO/HC emissions compared to conventional port injection systems.

2.3.3 EGR and Combustion Control for NO_x Reduction

Higher CR increases combustion temperature and NO_x formation. The use of cooled Exhaust Gas Recirculation (EGR), optimized ignition timing, and lean mixtures effectively reduces NO_x emissions while maintaining thermal efficiency improvements.

2.3.4 HCNG and Hydrogen Enrichment

Hydrogen enrichment increases flame speed and combustion stability, enabling lean combustion and improved efficiency at higher compression ratios. HCNG blends generally reduce CO and HC emissions but require proper control of NO_x formation.

2.3.5 Variable Compression Ratio (VCR) Technology

Variable Compression Ratio (VCR) engines dynamically adjust CR according to operating conditions. Higher CR can be used during low-load conditions for improved efficiency, while lower CR can prevent knock during high-load operation.

2.3.6 Advanced Modeling and Optimization Tools

Modern engine simulation tools and machine-learning-based models are increasingly used to predict optimum CR, combustion characteristics, and emission behavior. These tools reduce experimental effort and improve engine optimization processes.

2.3.7 Integrated Engine Optimization Approaches

Recent research suggests that the best performance and emission results are achieved by combining higher compression ratios with advanced technologies such as DI-CNG, EGR, HCNG blends, optimized ignition timing, and after-treatment systems.

2.4 Recent Developments Under BS VI and Euro 6 Regulations

Under BS VI and Euro 6 emission norms, CNG engine technology has advanced significantly toward cleaner and more efficient operation. Modern CNG engines typically operate with optimized compression ratios between 12:1 and 14:1 to achieve higher thermal efficiency with controlled emissions.

To comply with strict emission standards, manufacturers employ:

1. Cooled Exhaust Gas Recirculation (EGR) systems for NO_x reduction.
2. Advanced three-way catalytic converters for methane oxidation.
3. Closed-loop fuel control and precise air-fuel ratio management.
4. Direct Injection CNG (DI-CNG) systems for improved combustion.
5. Variable Valve Timing (VVT) and Variable Compression Ratio (VCR) technologies.
6. Advanced Electronic Control Units (ECUs) with OBD-II monitoring systems.
 - a. These developments improve engine efficiency, reduce emissions, and support the use of CNG as a cleaner alternative fuel for sustainable transportation.

III. IDENTIFIED RESEARCH GAPS

3.1 Limited Indian Context Studies: Most existing work focuses on European or generic CNG compositions. Very few studies consider Indian CNG quality, ambient conditions, and BS6 emission standards, which influence combustion and emission behaviour.

3.2 Narrow Experimental CR Range: Many experimental studies test only two or three fixed compression ratios (e.g., 9:1 and 12:1), leaving uncertainty about the optimum CR range (10–16:1) for maximum efficiency without knock.

3.3 Lack of Combined Performance–Emission Correlation: Studies often emphasize either performance or emission parameters individually. A comprehensive correlation between **BTE, BSFC, NO_x, CO, HC, and CO₂** across variable CRs is missing.

3.4 Insufficient Real-World Operating Condition Data: Most tests are conducted at constant speed and full load, ignoring part-load and transient driving conditions typical of city driving and fleet operation.

3.5 Minimal Work on DI-CNG and VCR Integration: Although Direct Injection (DI) and Variable Compression Ratio (VCR) technologies show promise, systematic experimental validation on CNG engines is limited and requires optimization of timing, mixture formation, and CR.

3.6 Limited Use of Hybrid Modeling: Few studies combine 1-D simulation (GT-Power, MATLAB) with experimental validation, which could reduce testing effort and improve prediction accuracy for CR optimization.

3.7 Emission–Aftertreatment Interaction Unclear: The combined effect of higher CR operation and catalytic aftertreatment (Euro 6/BS6) on methane slip and NO_x control remains insufficiently addressed.

3.8 Sustainability Perspective Missing: There is minimal integration of fuel economy gains, emission benefits, and lifecycle CO₂ reduction into a unified evaluation framework for CNG engines under high CR operation.

3.9 Potential Contributions in the Present Work

The present study aims to contribute both **scientifically** and **technologically** to the optimization of CNG engine performance under BS6 conditions through systematic analysis of **compression ratio (CR) variation**.

3.10 Comprehensive Experimental–Modeling Approach: The work will generate experimental data on performance (BTE, BSFC, torque, power) and emissions (CO, HC, NO_x, CO₂) at multiple CR settings, complemented by 1-D simulation or analytical modeling to predict trends beyond the tested range.

3.11 Identification of Optimum Compression Ratio: By testing within a wider CR range (e.g., 9:1–15:1), the study will establish an optimum CR that offers the best trade-off between thermal efficiency, fuel economy, and emission compliance for CNG operation.

3.12 Performance–Emission Correlation Framework: The project will develop an integrated performance–emission relationship to understand how CR affects combustion quality and pollutant formation, providing valuable reference data for future CNG engine calibration.

3.13 Applicability to Indian BS6 Conditions: Using locally available CNG fuel and considering Indian ambient conditions, the findings will support **domestic engine developers** in tuning CNG engines for BS6 norms with improved fuel economy and reduced emissions.

3.14 Knowledge Advancement: The outcomes will contribute new insights into combustion dynamics, knock limits, and emission characteristics at varying CRs, enriching academic understanding and aiding industry transition toward high-efficiency, low-carbon CNG mobility.

IV. PROBLEM DEFINITION

Compressed Natural Gas (CNG) has emerged as a clean alternative fuel for internal combustion engines due to its high octane rating and low carbon emissions. However, optimizing engine compression ratio (CR) for CNG operation remains a critical challenge. Increasing the CR generally improves thermal efficiency and reduces fuel consumption, but it also elevates in-cylinder pressure and temperature, which can lead to engine knock and increased NO_x emissions. Most existing studies have focused on limited CR ranges or specific engine types, often under controlled laboratory conditions, without considering Indian CNG composition, BS6 emission norms, and real-world operating conditions. Consequently, there is insufficient understanding of how varying the compression ratio affects combustion stability, performance characteristics, and emission behavior in modern BS6-compliant CNG engines. Therefore, a systematic experimental and analytical study is required to evaluate and optimize the compression ratio to achieve an ideal balance between engine performance, fuel efficiency, and emission control. This research seeks to address this gap by analyzing the influence of different CRs on the performance, combustion, and emission parameters of a dedicated CNG engine under varying load and speed conditions.

V. METHODOLOGY

The present study aims to analyze and optimize the effect of compression ratio (CR) on the performance and emission characteristics of a CNG-fueled spark-ignition engine through a combined experimental and analytical approach.

5.1. Methods

5.1.1 Engine selection-Which & Why ?

Engine should balance the experimental control, cost and relevance: single-cylinder, four-stroke, air-cooled or water-cooled spark-ignition (SI) test engine convertible to CNG.

Why single-cylinder?

1. Easier to modify for variable compression ratio (VCR).
2. Simpler access for in-cylinder pressure transducer and optical/diagnostic ports.
3. Lower fuel and instrumentation cost; easier to run repeatable steady-state points.
 - a. Minimum desirable specifications:
4. Displacement: **200–500 cc** (single cylinder)- adequate for steady-state mapping and common in university labs.
5. Rated speed: **1500–3000 rpm** Test at low to medium speeds typical of vehicle operation.
6. Compression ratio: base CR \approx **8.5–10:1**-so we can extend to higher CRs for CNG
7. Provision for adaptable head/piston design (removable head / replaceable pistons).
8. Intake port suitable for port-fuel injection or retrofit for gaseous fuel supply.
 - a. If multi-cylinder is available and modifiable, We can use it, but modifications (VCR) and measuring in-cylinder pressure on one cylinder will be more complex.

But, Done with multicylinder engine 4- cylinder because of easily available for us.

5.1.2 Methods to vary compression ratio

1. Replaceable Piston Crowns / Different Pistons

- Machine or procure pistons with different crown heights to give discrete CRs (e.g., 9:1, 11:1, 13:1, 15:1).
- Pros: Accurate, repeatable; retains combustion chamber geometry.
- Cons: Cost and machining time.

2. Cylinder Head Gasket / Spacer Method

- Use head gasket stacks or metal spacers to alter clearance volume.
- Pros: Cheap, easy to implement for small CR steps.
- Cons: Less precise; changes squish/quench area — note and report geometry changes.

3. Adjustable Combustion Chamber Insert

- Insert different volume plugs into the head or piston recess.
- Pros: Moderate accuracy, less piston machining.
- Cons: Requires precise sealing, careful design.

4. Eccentric Sleeve or Pivoting Head (VCR Mechanism)

- Mechanical VCR kits (complex) that change stroke/clearance dynamically.
- Pros: Allows continuous CR variation.
- Cons: Complex design, reliability and cost concerns for student project.

5.1.3 Fuel system for CNG

- Used regulated compressed natural gas (CNG) supply with a pressure regulator and mass flow meter (or thermal gas flow meter) for accurate fuel flow measurement.
- For port injection: use a calibrated gas injector/nozzle or supply through the intake manifold with measured flow.
- For DI-CNG experiments (advanced): retrofit a gas direct injector and high-pressure rail — complex and may need manufacturer help.

5.1.4 Safety & purity

- Used a certified CNG cylinder and regulator.
- Record gas composition (methane number or composition) from supplier or analyze with GC if available; document for reproducibility.

5.1.5. Ignition & control

- Used an adjustable ignition timing unit (ECU or programmable ignition) to vary ignition advance/retard.
- Spark plug: use standard heat range recommended but consider high-energy ignition module for lean mixtures.
- Used a programmable ECU to control spark timing map for each CR

5.1.6. Instrumentation

Performance:

- **Dynamometer:** Eddy-current or water brake with torque & speed measurement (accuracy $\pm 1-2\%$).
- **Fuel/Flow:** Mass flow meter for CNG (thermal mass flow meter or coriolis for gaseous fuels) with suitable range.
- **Air flow:** Orifice / hot-wire / mass air flow meter to measure intake air.
- **Combustion:**
- **In-cylinder pressure sensor** (piezoelectric) — high frequency response (≥ 100 kHz), calibrated. Install in cylinder head with appropriate wiring and charge amplifier.

- **Crank angle encoder/encoder:** 0.1° or better resolution synchronized with cylinder pressure.
- **Emissions:**
- **5-gas analyzer:** measures CO, HC (ppm), NO_x, CO₂ and O₂; accuracy per manufacturer (NO_x ±2 ppm typical).
- If possible, methane-specific analyzer for methane slip (important for CNG).
- **Others:**
- Exhaust gas temperature (thermocouple), intake manifold pressure (MAP), coolant temp, oil temp, ambient conditions (T, P, humidity), and vibration/knock sensor (optional).
- **5.1.7. Data acquisition**
- **DAQ system** with adequate sampling rates:
- In-cylinder pressure: sample at 0.1° CA resolution or higher; typical sample frequency 20–50 kHz depending on RPM.
- Analog channels for thermocouples, pressures at lower sample rates.
- Used a data acquisition software capable of crank-angle-based averaging and heat-release calculation.
- AVL PUMA measurement system which is proven for emission & performance.
- **5.1.8. Test cell setup & calibration**
- Mounted engine on a rigid test bed and connect to dynamometer with flexible coupling and torque sensor.
- Ensured proper cooling circuit and exhaust routing to analyzer.
- Calibrate all sensors before tests: DAQ, torque, flow meters, pressure transducer (static & dynamic checks), gas analyzer (span/zero) using calibration gases.
- Checked for gas leaks (soap solution, gas detectors) -CNG safety critical.

5.1.9. Test matrix

Compression ratios: 9:1, 11:1, 13:1, 15:1 (or as achievable).

Speeds (RPM): 1500, 2000, 2500 & so on Loads (Brake mean effective pressure / torque): 25%, 50%, 75%, 100% of max (or corresponding brake torque steps).

Ignition timings: optimum for baseline CR; test ± some degrees for knock margin study.

Optional: EGR levels (0%, 10%, 20%) for NO_x mitigation experiments. Each test point: run for steady state for sufficient time (e.g., 3–5 min) and average last 60 s; repeat 3 runs for repeatability.

5.1.10. Data processing & analysis

Primary analyses to perform

- Compute Brake Power, BTE, BSFC, and thermal balance.
- From in-cylinder pressure: compute IMEP, P_{max}, combustion phasing (CA50), heat release rate (HRR), and knock indicators (pressure rise rate, PPRR).
- Emissions: CO, HC, NO_x, CO₂ trends vs CR, load, timing.
- Statistical uncertainty analysis: report measurement uncertainty for torque, flow, pressure, and derived quantities (propagate errors).
- Present maps/plots: BTE vs CR, BSFC vs CR, NO_x vs CR, CA50 vs CR, HRR curves comparison.

5.2. Bharat Stage VI.2 (BS 6.2) Emission Standards

BS 6.2 standards, introduced in India, align closely with Euro VI but include methane-specific regulations due to CNG usage. Limits for passenger vehicle M & transport vehicle N categories for Small commercial vehicles CNG SI engines are typically below 3.5 tons are as follows.

Table No 01: BS 6 Emission Standards for Vehicles category N < 3.5 tons

Emission	CO	NO _x	NMHC	THC
Unit	mg/km	mg/km	mg/km	mg/km
BS 6 Limits	1810	75	90	130

These regulations required close control of λ , efficient TWCs, and advanced measurement systems (ETAS INCA, HORIBA MEXA, FTIR analyzers).

5.3 Experimental Modelling

- Predict how **compression ratio (CR)** affects engine performance (BTE, BSFC, IMEP, torque) and combustion metrics (CA50, HRR, Pmax).
- Predict emissions (NO_x, CO, HC, CO₂) trends with CR, equivalence ratio, ignition timing and EGR.
- Reduce experimental matrix by pre-screening CR/ignition/EGR combinations and explain observed trends.
- Provide a validated model for extrapolation beyond tested CRs.

5.3.1. Levels of modelling

A. 0-D/Quasi-steady thermodynamic model (MATLAB)

- Quick tool for ideal Otto cycle comparisons and first-order sensitivity (CR effect on theoretical efficiency).
- Equations: Otto cycle efficiency $\eta = 1 - 1/CR^{(\gamma-1)}$ (use variable γ with temperature), basic mass & energy balances.
- Use for baseline expectations and to compute clearance volume changes when you change CR.

B. Zero-/One-Zone combustion model (crank-angle resolved, MATLAB/Python)

- Solve in-cylinder pressure using first-law (Lindstedt/Wiebe heat-release): $dP/d\theta = (\gamma/(V(\theta))) [\dot{Q}_{net} - \gamma P dV/d\theta]$ form with appropriate discretization.
- Use empirical Wiebe function for mass fraction burned (MFB): $MFB(\theta) = 1 - \exp[-a((\theta - \theta_0)/\Delta\theta)^{(m+1)}]$.
- Inputs: CR, swept volume, valve timing, initial temperature/pressure, equivalence ratio, ignition timing.
- Outputs: P- θ , IMEP, CA10/50/90, HRR, peak pressure and pressure rise rates (knock proxy).

C. 1-D gas-exchange and cycle simulation (GT-Power / Ricardo WAVE / AVL BOOST)

- Build engine geometry (intake/exhaust runner lengths, valve areas), include intake dynamics and heat transfer.
- Include fuel injection model (port vs DI), ignition map, and EGR loop.
- Implement detailed combustion model: Wiebe/Wiebe or EKF-based submodels; advanced options: turbulent flame speed model (Zimont) or SI combustion models in GT-Power.
- Implement NO_x model (extended Zeldovich/via empirical correlations) and CO/HC via equilibrium or surrogate kinetics.
- Run full speed-load maps for each CR step; perform parameter sweeps.

D. (Optional) 3-D CFD / Combustion (CONVERGE, OpenFOAM, ANSYS Fluent)

- Use for localized phenomena (knock hot-spots, mixture stratification in DI). Heavy resource requirement.
- Solve RANS/LES with detailed chemical mechanism for methane (reduced mechanisms), turbulence-chemistry interaction (Eddy Dissipation Concept, Flamelet models).
- Use only for 1–2 critical cases (e.g., highest CR + DI) to explain anomalies.

5.3.2. Governing equations & sub-models

- **Mass conservation:** $dm/dt = \dot{m}_{in} - \dot{m}_{out}$.
- **Energy conservation (first law) for cylinder control volume:** $dU/dt = \dot{Q}_{in} - \dot{W} + \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out}$. Convert to crank-angle form for P- θ modelling.
- **State equation:** $P V = m R T$ (use variable gas properties).
- **Heat transfer:** Woschni or Hohenberg correlation for in-cylinder heat transfer: $\dot{Q}_{ht} = h A (T_g - T_w)$.
- **Combustion model:** Wiebe/Vibe function with calibrated parameters (a, m, $\Delta\theta$).
- **NO_x formation:** Extended Zeldovich mechanism (thermal NO): $d[NO]/dt \approx f(T, O, N)$ or use empirical: $NO_x \approx A * \exp(-B/T_{max}) * (\text{residence time})$ modified by O₂ concentration and EGR.
- **CO/HC:** Use empirical correction based on equivalence ratio, incomplete combustion factor, or equilibrium chemistry with correction for finite rate (if detailed kinetics available).
- **Knock indicator:** Maximum pressure rise rate (dP/d θ) or PPRR (pressure per crank degree) threshold or auto-ignition delay from Arrhenius expression using fuel octane/methane number surrogate.

5.3.3. Calibration & validation strategy

- **Calibration:** Use a baseline experimental data set (one CR, several loads) to tune combustion (Wiebe), heat transfer (Woschni), and NO_x empirical constants.
- **Cross-validation:** Validate against other CR values and operating points not used for calibration. Aim for <5% error in IMEP/BTE and <15–20% in emissions (typical modeling tolerances).
- **Knock modeling:** Compare predicted knock indicators (max dP/d θ or auto-ignition delay) with observed onset of knocking in experiments (audible, pressure spikes).

5.3.4. Experimental Specification Details

5.4 Test Details

5.4.1 Test Engine Description

The experimental investigations are carried out on a four-cylinder, multi-point fuel injection (MPFI) spark ignition engine designed for bi-fuel operation (CNG and Petrol). The engine is coupled with an eddy current dynamometer for applying controlled load and for performance measurement. This setup facilitates a detailed study of how variation in compression ratio (CR) influences engine efficiency, combustion behavior, and exhaust emissions under different fuel conditions.

5.4.2 Engine Specifications

Table No 02: Engine Specification

Parameter	Specification
Make	Research-grade MPFI SI Engine
Type	4-stroke, water-cooled, MPFI
Number of Cylinders	4
Bore × Stroke	86 mm × 90 mm
Swept Volume	2089 cc
Rated Power	101 HP
Fuel Type	Petrol / CNG (bi-fuel)
Compression Ratio (CR)	Variable (9:1 to 15:1 adjustable)
Ignition System	Electronic ignition
Cooling System	Water-cooled (closed-loop)
Loading Device	Eddy current dynamometer
Speed Range	1000–5000 rpm

5.4.3 Fuel Properties

Table No 03: Fuel Properties

Property	Petrol	CNG
Chemical Formula	C ₈ H ₁₈	CH ₄
Carbon Composition (%)	85–88	75
Hydrogen Composition (%)	12–15	25
Density (kg/m ³)	750	0.72
Octane Number	89–94	120+
Latent Heat of Vaporization (kJ/kg)	9.94	12.79
Auto-Ignition Temperature (°C)	230	540
Calorific Value (kJ/kg)	44,000	45,000
Stoichiometric Air–Fuel Ratio (by weight)	14.7	17.2

5.4.4 Test Bed Arrangement

The engine is securely mounted on a rigid base frame and directly coupled to the eddy current dynamometer using a flexible coupling to minimize vibration and misalignment.

A two-stage gas regulator supplies CNG from a high-pressure cylinder to the MPFI system at constant pressure. Air flow is measured using an air box with an orifice plate and manometer, and CNG flow rate is recorded using a mass flow meter.

The exhaust gas analyzer measures CO, CO₂, HC, O₂, and NO_x concentrations, while thermocouples monitor the temperatures of exhaust, cooling water, and inlet air. The system allows accurate monitoring of all key parameters to study the effect of compression ratio variation.

5.5 Experimental Setup

5.5.1 Experimental Layout

The experimental setup developed for this project is a BS 6.2-compliant multi-cylinder CNG spark-ignition engine test bench equipped with an advanced electronic control system and emission measurement instrumentation. A schematic layout of the setup is shown in Figure 1. It integrates subsystems for intake air management, fuel supply, ECU calibration, emission analysis.

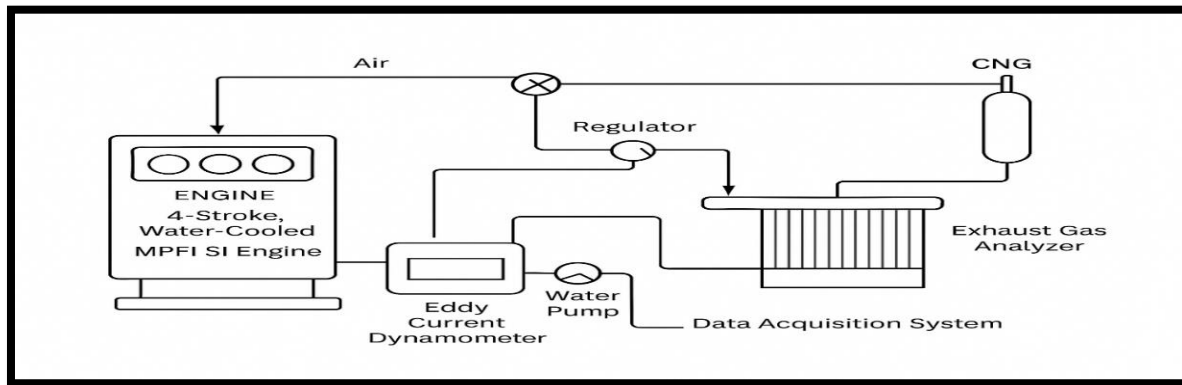


Figure 1: Schematic layout of the Experimental Setup

The experimental setup consists of the following 5 five major systems:

- 4-Cylinder Turbocharged BS6.3 CNG Engine
- Air intake System.
- Fuel Supply System.
- Exhaust and three-way catalytic System with lambda measurement.
- Dyno Controller, Data Acquisition, and Emission Measurement System.
- Electronic Control Unit (ECU) & Engine ECU Calibration Software.

5.5.2. Test Engine

A four-cylinder turbocharged CNG spark-ignition engine emission compliance with BS 6.2. Air Intake System: Equipped with electronic throttle control, intake manifold sensors for accurate measurement. Features a closed-loop lambda control, electronic throttle, and port fuel injection for precise CNG metering for stable and efficient performance. The exhaust system includes heated O₂ sensors, a TWC with washcoat, while the ECU continuously adjusts λ to monitor and control CO, NO_x, THC, and CH₄ emissions effectively. Engine specifications such as displacement, compression ratio, number of cylinders, and rated power will be documented in the test matrix.

5.5.3. Electronic Control Unit (ECU) & Engine ECU Calibration Software

The ETAS INCA 7.2 is a powerful calibration, measurement, and diagnostics software used for ECU calibration and engine testing. It enables real-time data acquisition, parameter tuning, and analysis through interfaces like CAN, LIN, and XCP. With a user-friendly interface, ECU ensures closed-loop air-fuel ratio control via a wideband lambda (O₂) sensor. Calibration maps will be modified in controlled increments to generate λ variations between 0.95 (rich) and 1.05 (lean). It integrates smoothly with systems like AVL PUMA, HORIBA MEXA-ONE, and DynoRoad 220 kW, making it essential for modern automotive calibration and research applications

5.5.4. Engine Transient Dynamometers Controller & Data Acquisition System.

The test Engine, mounted on a transient dynamometer that allows precise control of engine speed and load during steady-state testing. Cooling is managed using a radiator, fan, and coolant circuit, while exhaust gas temperature and manifold pressure are monitored in real-time. The engine is operated under BS 6.2 steady-state points, typically in the range of 1500–3000 rpm, at multiple loads.

The AVL PUMA dyno controls system is an advanced test automation and data acquisition software used for powertrain testing. It provides real-time control of parameters such as speed, torque, and load, ensuring high precision and repeatability. When integrated with a DynoRoad 220 kW dynamometer, it automates both steady-state and transient tests. It features a user-friendly interface, supports multiple communication protocols (CAN, Ethernet, XCP/CCP), and includes strong safety and fault management systems. With its powerful data analysis and integration capabilities.

5.5.5. Emission Measurement System

Exhaust gas analyzed and emissions will be measured using HORIBA MEXA ONE analyzers compliant with BS 6.2 as recommended in AIS 137 Part 4 (CMVR) emission testing standards.[22] The HORIBA MEXA-ONE is a modular and high-precision emission measurement system. It accurately measures important exhaust gases such as CO, CO₂, NO_x, O₂, and HC using advanced technologies like NDIR, CLD, and FID. Compact and flexible, it easily integrates with test automation systems like AVL PUMA for synchronized operation.

The system offers fast response, reliable data, and compliance with global emission standards such as BS VI / Euro 6, making it ideal for research, calibration, and emission certification testing in modern automotive labs.

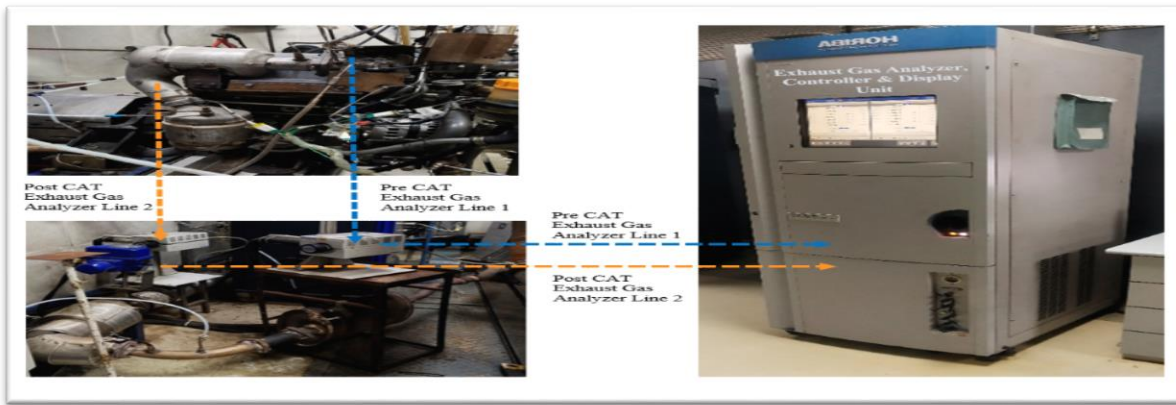


Figure 2: Horiba Exhaust Gas Analyzer & Controller

5.6 Test Setup Configuration & Specification

5.6.1. Table No. 05: Test Setup configuration & Testing Specification

Sr. No	Configuration	Specifications
1	Engine Type	4- Cylinder Vertical Inline Turbocharged Intercooler Engine, Cubic capacity 2.2 liters
2	Engine Rating	Power - 101 PS @ 5000 rpm: Torque - 140 Nm @ 3000 - 3500 rpm
3	TWC Type	Reduction & Oxidation Type: Substrate Honeycombed Ceramic: Relative Concentrations coating- Pt 92 %, Rh 8%: Metallic casing with Insulation blanket
4	Oxygen Sensor Pre TWC	Wideband lambda sensor -Make Bosch LSU 4.9
5	Oxygen Sensor Post TWC	Wideband lambda sensor -Make Bosch LSU 5.1
6	Lambda Meter	ETAS 631.1 - Lambda meter with two signal outputs
7	Fuel Flow Meter	Endress + Hauser Model 83A04-GSVWBABABCAA
8	Air Flow Meter	ABB - Model Sensy flow P
9	Dynamometer	AVL - Dyno road 220kW With Dyno operating controller PUMA
10	Exhaust Analyzer Gas	HORIBA - MEXA ONE D2 EGR

11	ECU Controller	ETAS INCA 7,2 – ES582 CAN communication device with Test ECU Controller 12 Volt.
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VI. RESULTS AND CONCLUSION

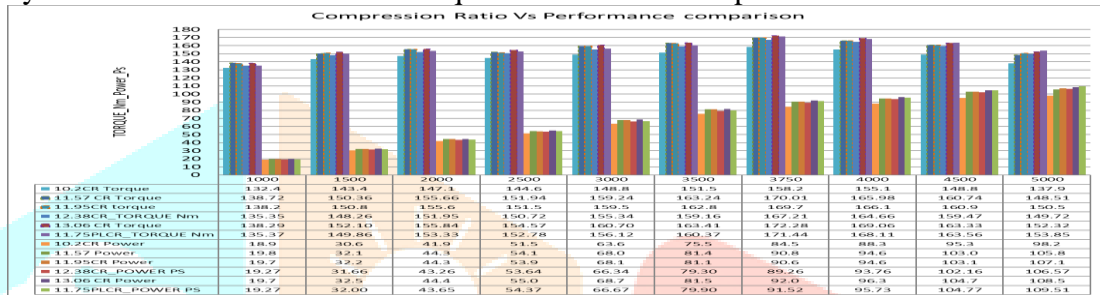
The following parameters are taken into consideration for finding the optimum Compression Ratio (CR).

- Power and Torque
- BSFC
- Carbon Monoxide (CO) emissions
- Nitrogen Oxide (NO2) emissions (NO2)
- Total Hydrocarbon (THC)
- Brake Thermal Efficiency (BTE)
- In-Cylinder Pressure (ICP)

1. Power & Torque

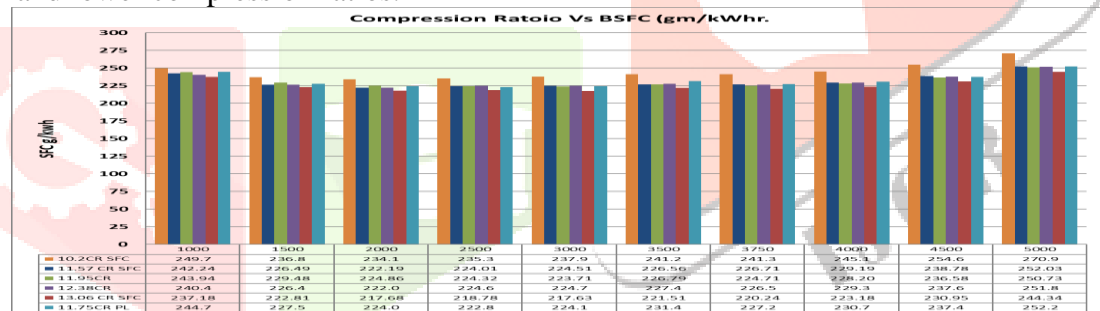
-Chart shows the comparison of Power and Torque at different RPM and compression ratio.

-Significantly the 12.38 CR shows better Torque and Power as compared to the other CR.



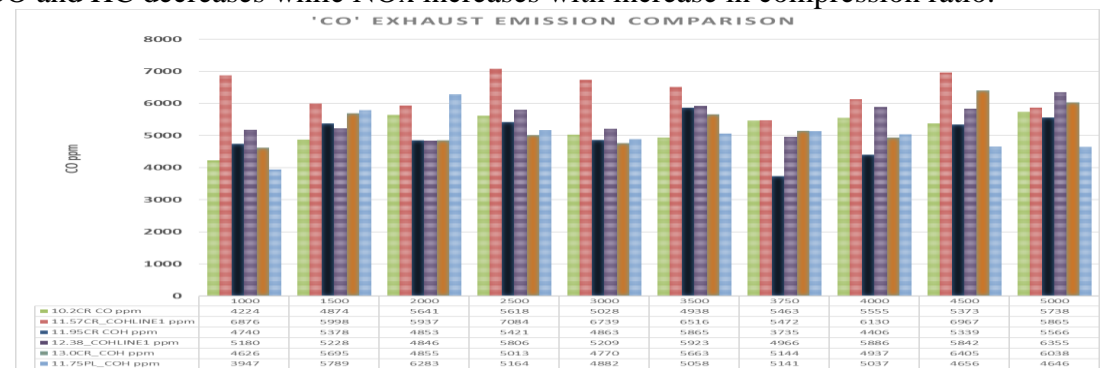
2. BSFC (gm/kW.Hr)

-The BSFC values for the selected compression ratio of 12.38 were found to be optimal when compared with both higher and lower compression ratios.



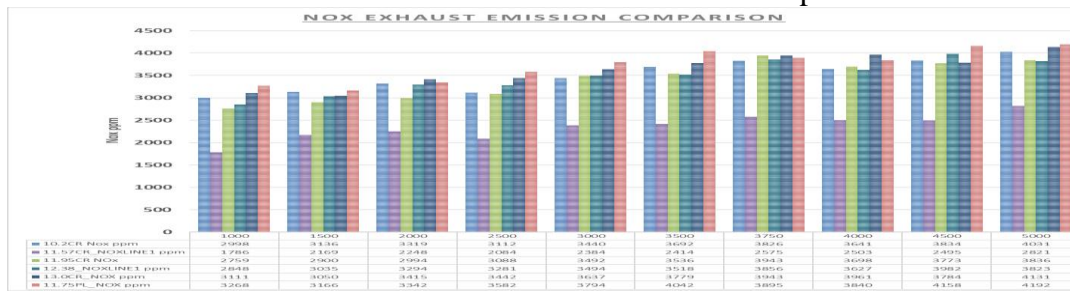
3. Carbon Monoxide (CO) emissions

-Exhaust CO and HC decreases while NOx increases with increase in compression ratio.



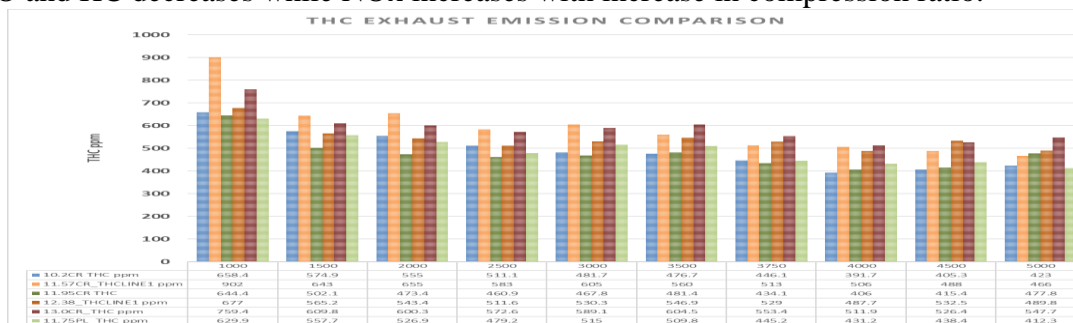
4. NOx Emission

-Exhaust CO and HC decreases while NOx increases with increase in compression ratio.

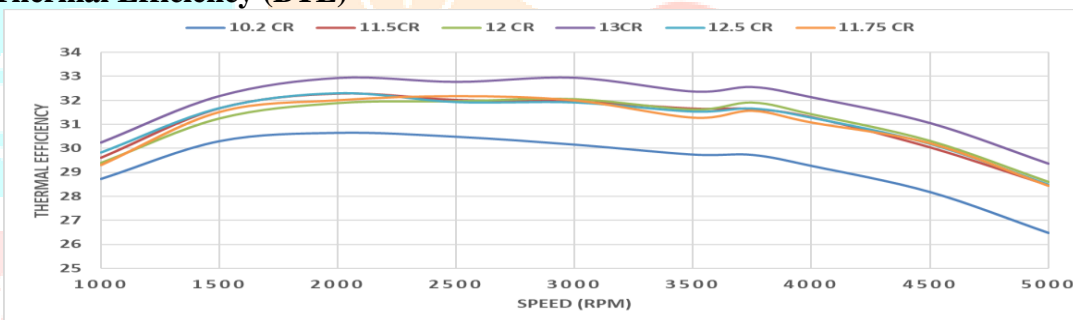


5. Total Hydrocarbon (THC)

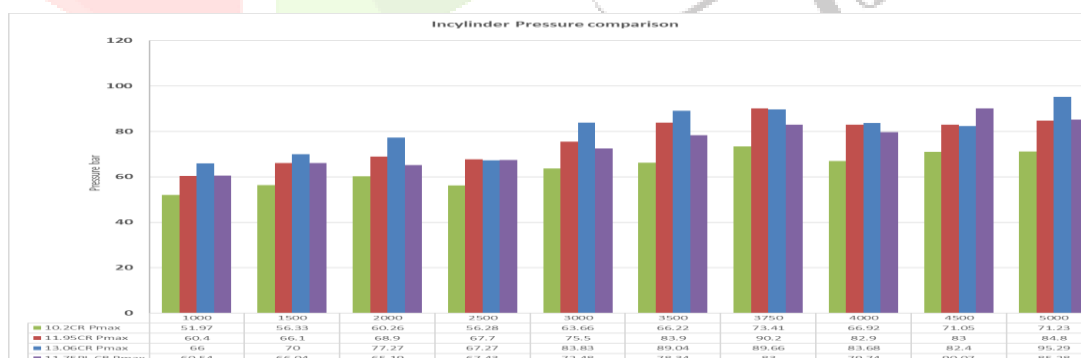
-Exhaust CO and HC decreases while NOx increases with increase in compression ratio.



6. Brake Thermal Efficiency (BTE)



7. In-Cylinder Pressure (ICP)



VII. CONCLUSION.

1. Increase in compression ratio increases the brake power, torque, brake thermal efficiency, brake mean effective pressure and decreases the specific fuel consumption.
2. The overall performance of the CNG engine was very good and also showed performance equivalent to base diesel engine.
3. Exhaust CO and HC decreases while NOx increases with increase in compression ratio.
4. Based on the test results, compression ratio 12:1 is proposed as an optimum compression ratio for dedicated CNG engines

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