



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

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ABSTRACT:

This study investigates the effect of compression ratio on the performance of a dedicated CNG engine. Compression ratios of 10 to 13 and engine speeds ranging from 1000 to 5000 rpm were analyzed to determine the optimum compression ratio. The results show that increasing the compression ratio improves engine performance parameters such as power, torque, brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC). Due to lower emissions and cleaner combustion, CNG engines are becoming a sustainable alternative to conventional fuels. The study concludes that an optimum compression ratio enhances the efficiency and overall performance of dedicated CNG engines.

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

1. INTRODUCTION.

1.1 Worldwide Scenario

Natural Gas Vehicles (NGVs), mainly CNG-based, are widely used across countries such as China, India, Iran, Pakistan, and Argentina. Due to its high octane number, CNG allows higher compression ratios, improving thermal efficiency and reducing fuel consumption. Studies show that increasing compression ratio improves power, torque, brake thermal efficiency, and BSFC up to an optimum limit. Emissions like CO and HC generally decrease, while NO_x may increase due to higher combustion temperatures. Modern technologies such as Direct Injection (DI), EGR, optimized spark timing, and HCNG blends help achieve better efficiency with controlled emissions. Further research is needed on CR optimization, knock analysis, and performance under varying operating conditions.

1.2 Scenario in India

India has witnessed rapid growth in CNG vehicles, reaching nearly 7.5 million vehicles by 2025. Increasing CNG infrastructure and stricter emission norms have boosted adoption in passenger vehicles, taxis, buses, and three-wheelers. Indian driving conditions, fuel quality variations, and high ambient temperatures make engine optimization important. Most Indian CNG vehicles are modified petrol engines, creating a need for dedicated high-compression CNG engine research. Limited Indian-specific studies are available on compression ratio effects under local conditions, providing strong research opportunities.

1.3 Scope of the Project

The project focuses on studying the effect of compression ratio on the performance, combustion, and emission characteristics of a CNG engine using experimental and modeling approaches.

Scope Includes:

1. Experimental analysis of engine performance at different compression ratios.
2. Measurement of parameters such as brake thermal efficiency, power, torque, BSFC, and emissions.
3. Development of thermodynamic/simulation models using MATLAB or GT-Power.
4. Determination of the optimum compression ratio for better efficiency and lower emissions.
5. Evaluation of engine behavior under Indian operating conditions.
6. Providing recommendations for dedicated CNG engine development.

1.4 Purpose of the Study

The purpose of this study is to analyze the effect of compression ratio on the performance and emission characteristics of CNG engines through experimental and simulation methods. The study aims to improve engine efficiency, fuel economy, and emission control while supporting the development of cleaner and sustainable transportation systems. It also provides useful insights for researchers, manufacturers, and policymakers working on dedicated CNG engine technologies.

1.5 Objectives of the Project**Main Objective**

To study the influence of compression ratio on the performance, combustion, and emissions of a CNG engine.

Specific Objectives

1. To analyze the effect of compression ratio on brake power, BTE, and BSFC.
2. To study combustion characteristics using pressure and heat release analysis.
3. To evaluate exhaust emissions such as CO, HC, NO_x, and CO₂.
4. To develop and validate a simulation model using MATLAB or GT-Power.
5. To determine the optimum compression ratio for efficient CNG engine operation.
6. To compare results with existing literature and global studies.
7. To provide recommendations for efficient dedicated CNG engine design.

2. LITERATURE REVIEW.**2.1 Overview**

2.1.1. Thermodynamic basis and expected effects of compression ratio (CR): Compression ratio is a primary thermodynamic parameter that strongly influences thermal efficiency in spark-ignition engines: higher CRs increase the theoretical Otto-cycle efficiency by expanding the pressure–temperature swing and extracting more work per cycle. For gaseous fuels such as CNG (high methane content, high octane number), the higher knock resistance compared to gasoline allows safe operation at elevated CRs, potentially improving brake thermal efficiency (BTE) and lowering brake specific fuel consumption (BSFC). However, increases in in-cylinder peak pressure and temperature that accompany higher CRs tend to promote NO_x formation, creating the classical trade-off between efficiency and regulated emissions. [sciencedirect.com+1](https://www.sciencedirect.com)

2.1.2. Experimental evidence: CR → performance trends: Multiple steady-state and variable-CR experimental studies report consistent trends: raising CR generally increases indicated and brake thermal efficiency and reduces specific fuel consumption up to an engine-dependent optimum. For example, a controlled study that varied CR from ~9:1 to 16:1 on a CNG-operated engine recorded notable gains in indicated thermal efficiency and reductions in BSFC until knock or diminishing returns limited further increases. These studies also show that the numerical value of the “optimal” CR depends on engine geometry, fueling method (port vs DI), ignition timing, and operating load. [2024.sci-hub.box+1](https://www.sci-hub.com)

2.1.3. Emissions response to increased CR: The emission response is more nuanced. Studies reviewing gaseous-fuel engines find that CO and unburned hydrocarbons typically decrease with improved combustion at higher CRs, while NO_x tends to rise because of increased combustion temperatures and earlier peak heat release. Several authors note that lean operation, exhaust gas recirculation (EGR), or fuel enrichment strategies can be paired with higher CRs to mitigate NO_x while preserving efficiency gains. The literature therefore emphasizes combined strategies rather than CR change in isolation to meet emission targets. [MDPI+1](https://www.mdpi.com)

2.1.4. Role of fueling method: Port-injection vs direct-injection (DI) CNG: Direct injection (DI) of CNG alters mixture formation and charge cooling characteristics, allowing later injection and higher volumetric efficiency, which in turn helps suppress knock and improves controllability at high CRs. Numerical and experimental investigations of DI-CNG engines have demonstrated viability of relatively high CRs (often ≥13:1 and in some reports approaching 15–16:1) with superior thermal efficiency and

lower CO/HC emissions than port-injection systems; however, DI operation may slightly increase NO_x unless countermeasures (EGR, after-treatment) are applied. This makes DI-CNG an attractive path for exploiting the high octane of natural gas. [saemobilus.sae.org+1](https://saemobilus.sae.org)

2.1.5. Modelling and simulation studies: Complementary to experiments, 1-D cycle models and CFD/combustion simulations have been widely used to predict CR effects across broader operating envelopes and to analyze knock margins, in-cylinder pressure traces, and heat-release rates. Simulation studies confirm the experimentally observed trends and are especially useful for sensitivity analysis (CR vs spark timing, EGR fraction, equivalence ratio). They also help design test matrices by indicating regions of likely knock or unstable combustion before running hardware tests. [pubs.aip.org+1](https://pubs.aip.org)

2.1.6. Alternative strategies and blends (HCNG, hydrogen enrichment): Several studies explore hydrogen enrichment (HCNG) and small amounts of hydrogen or other high-reactivity additives to accelerate combustion and allow either lower CR with maintained power or higher CR with reduced knock risk. Such blends can shift the trade-off curve by improving flame speed and reducing unburned hydrocarbons, though their effects on NO_x depend on the final peak temperatures and mixture distribution. This line of work is relevant where SOPO (safety, storage, and infrastructure) constraints allow blended fuels. [MDPI+1](https://mdpi.com)

2.2 Gaps and research opportunities

Despite consistent global findings, important gaps remain: (a) many experimental studies use limited engine geometries or steady-state points and do not map transient/part-load urban cycles typical of many CNG fleets; (b) comparative datasets for port-injection vs DI across the same engine platform and CR sweep are sparse; (c) knock onset at high CR with real-world CNG compositions (fuel variability) is under-explored; and (d) India-specific studies that tie CR optimization to local fuel composition, ambient conditions, and driving cycles are limited. Addressing these gaps—by combining a systematic CR sweep, in-cylinder pressure analysis, emission mapping, and validated cycle simulations—will produce practically useful recommendations for dedicated CNG engine design.

2.3 CR effects on performance & emission on CNG engines

2.3.1 Exploiting CNG's knock resistance -pushing CR higher: Because natural gas has a high octane/methane number, researchers have safely increased compression ratios well above conventional petrol values to extract higher thermal efficiency and lower BSFC. Recent experimental and numerical studies report practical CR ranges up to about 15–16:1 for CNG spark-ignition engines with careful calibration, yielding measurable BTE gains. [ADS+1](https://ads.aip.org)

2.3.2 Direct injection (DI-CNG) widens the useful CR window: DI-CNG changes mixture formation and provides charge-cooling and late-injection benefits that reduce knock tendency and enable higher CR operation with improved efficiency and lower CO/HC compared with port injection. Multiple works show DI + optimized ignition timing can sustain CRs $\geq 13:1$ while improving BTE; the penalty is often a modest NO_x rise unless mitigated. [saemobilus.sae.org+1](https://saemobilus.sae.org)

2.3.3 EGR and combustion control to manage NO_x at high CR: A persistent issue when raising CR is higher in-cylinder temperatures → more NO_x. Advanced use of cooled EGR, combined with optimized spark timing and sometimes reduced equivalence ratio, has been shown to cut NO_x significantly (studies report large NO_x reductions with 10–30% EGR) while preserving much of the BTE advantage from higher CR. Simulation + experiments are commonly used to size EGR for given CRs. [sciedirect.com+1](https://sciedirect.com)

2.3.4 HCNG / hydrogen enrichment — faster combustion, higher CR tolerance: Hydrogen enrichment (HCNG) increases laminar flame speed and combustion stability, enabling leaner operation or allowing higher CRs with less knock and shorter burn durations. Recent studies find HCNG blends improve BTE and reduce CO/HC; NO_x behavior depends on peak temperatures and must be managed (often with EGR or retarded timing). [sciedirect.com+1](https://sciedirect.com)

2.3.5 Variable compression ratio (VCR) and adaptive control strategies: VCR hardware and control strategies allow dynamic CR adjustment to match operating conditions (e.g., high CR at cruise for efficiency, lower CR under high load or transient knock-prone conditions). Recent VCR research emphasizes controller design, mechanical robustness, and integration with ignition/boost/EGR control for optimal economy-emissions tradeoffs. [ResearchGate+1](https://researchgate.net)

2.3.6 Improved modelling, knock prediction and optimisation tools: Advances in 1-D cycle modelling (GT-Power/AVL/Matlab), coupled with empirical knock-models and limited CFD, enable faster CR sensitivity studies across full speed-load maps before costly experiments. Machine-learning assisted regression models have also been used to predict optimum CR and performance metrics from test data. These tools reduce experimental matrix size and help design mitigation strategies (EGR, spark timing, injection timing). [sciedirect.com+1](https://sciedirect.com)

2.3.7 Integrated approaches — combining CR increase with system-level fixes: The most promising practical paths combine higher CR with one or more of: DI-CNG, cooled EGR, optimized ignition maps, HCNG/H₂ enrichment, and after-treatment (SCR/oxidation) — producing net efficiency gains while meeting emissions targets. Studies emphasize that CR cannot be considered in isolation; engine architecture and control must be co-designed. saemobilus.sae.org+1

2.4 Recent Developments under new legislation BS VI and Euro 6

Under **Euro 6** and **BS 6** emission regulations, CNG engine technology has advanced toward cleaner combustion and higher efficiency through improved **compression ratio (CR) design** and **combustion control**. Modern CNG engines now use **optimized CR (typically 12:1–14:1)** to enhance thermal efficiency while maintaining low knock tendency.

To meet the stringent NO_x, CO, and HC limits, manufacturers employ:

- **Cooled EGR systems** to reduce NO_x formation at higher CRs.
- **Three-way catalytic converters** optimized for methane oxidation.
- **Precise fuel metering and closed-loop lambda control** for stoichiometric operation.
- **Direct-Injection CNG (DI-CNG)** systems that improve mixture formation and allow lean or stratified combustion.
- **Variable Valve Timing (VVT)** and **Variable Compression Ratio (VCR)** mechanisms for dynamic optimization under transient loads.
- **Advanced electronic control units (ECUs)** and **OBD-II compliance** for real-time emission monitoring.
- These developments enable CNG engines to achieve **higher efficiency, reduced carbon footprint, and full compliance** with **Euro 6 / BS 6 norms**, positioning CNG as a key transitional fuel toward low-emission mobility in India and globally.

3. 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**.

4. 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.

5. CONCLUSIONS:

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 NO_x 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 engine.

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7. REFERENCES

- [1]. Semin, Rosli Abu, A Technical Review of Compressed Natural Gas as an Alternative Fuel for Internal Combustion Engines, American J. of Engineering and Applied Sciences 1 (4): 302-311, ISSN 1941-7020.
- [2]. SAE Paper No. 2005-26-033-Gasoline To Gas – Revolution, S.Krishnan, D.S.Kulkarni and J.P. Mohite, Tata Motors Ltd., Pune, S.D.Rairikar and K. P. Kavathekar, The Automotive Research Association of India, Pune, India.
- [3]. Effect of the compression ratio on the performance and combustion of a natural-gas direct-injection engine J-J Zheng, J-H Wang, B Wang, and Z-H Huang - State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, People's Republic of China.

- [4]. SAE Paper No. 2013-26-0005 - Development of Three Wheeler CNG 501 - Vehicle with Improved Fuel Efficiency and Reduced CO2 Emissions- B J Shinde, S S Sane, Babu Borhade, Ashwin D'Souza and P Sutar, Piaggio Vehicles Pvt. Ltd., India.
- [5]. SAE Paper no. 2009-26-022–Development of a 2 Stroke CNG engine for 3-wheeler vehicle for the Indian market – Shanmugam, Anbukarasu, AS Babu, YR and Vinay Harne, TVS Motor Company.
- [6]. Ashok A. Mandal, Dr. R. S. Dalu, A Technical Review on Feasibility of CNG and GasolineEthanol blends in SI engine, International Journal of Emerging Technology and Advanced Engineering, Volume 2, Issue 12, December 2012.
- [7]. SAE Paper No:2015-01-168-Development of a Single Cylinder Dedicated CNG Engine for Small 4 Wheeler Commercial Vehicles- Girish Khairnar, Jagrit Shrivastava, Sachin Pande, Rohit Londhe, Yaser Hussaini, and Yogesh Ambekar Greaves Cotton, Ltd.
- [8]. Effect of the compression ratio on the performance and combustion of a natural-gas direct-injection engine J-J Zheng, J-H Wang, B Wang, and Z-H Huang - State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, People's Republic of China.
- [9]The Automotive Research Association of India (Research Institute of the Automotive Industry with the Ministry of Heavy Industries, Govt. of India) <https://www.araiindia.com>.
- [10] HORIBA - <https://www.horiba.com/ind/mobility/products/detail/>
- [11] AVL – <https://www.avl.com>
- [12] ETAS - <https://www.etas.com>

