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A Review on "Effect of Air–Fuel Ratio (λ) Variation on Combustion Parameters and Three-Way Catalyst Performance in CNG Engines."

Nishikant J. Gondane, M.Tech (Heat Power Engineering)
G H Raisoni College of Engineering and Management, Pune

Dipak. S. Patil (Guide)
Department of Mechanical Engineering,
G. H. Raisoni College of Engineering and Management, Pune

ABSTRACT:

The Bharat Stage 6.2 automotive emission norms draw attention to exploring alternative fuels like Compressed Natural Gas (CNG), which offers cleaner combustion and reduced emissions. However, maintaining the BS 6.2 emission compliance levels requires a fine balance between combustion stability and after-treatment performance.

The purpose of this review is to systematically analyze previous research related to the influence of air-fuel ratio on engine performance, emission formation, and catalyst conversion efficiency in spark-ignition CNG engines. The review spans from early experimental works in the 2000s to recent studies incorporating advanced control strategies, catalyst optimization, and BS VI calibration technologies.

Several studies have analyzed λ, but most either focus only on combustion or only on catalyst performance, or often use single-cylinder test engines or older measurement techniques. Very few studies combine λ variation, multi-cylinder engines, and BS 6.2-compliant emission testing. This review summarizes key findings from existing research, trends, identifies technological progress, discusses research gaps that remain unexplored, and highlights the need for integrated studies that link λ, engine combustion, and catalyst efficiency for modern CNG engines.

Keywords:- CNG engine, Air–Fuel Ratio (λ), NOx, Methane Slip, Three-Way Catalyst (TWC), ECU Calibration, air-fuel ratio, BS 6.2, emissions.

I. INTRODUCTION.

The automotive industry is undergoing a major transformation motivated by environmental concerns and strict emission regulations. Conventional fuels such as gasoline and diesel contribute substantially to harmful pollutants, including CO, NO_x, HC, and PM. To mitigate these effects, researchers and industries have been exploring alternative fuels that can offer lower emissions with comparable performance.

Among these alternative fuels, compressed natural gas (CNG) has gained prominence due to its high octane rating, low carbon-to-hydrogen ratio, and cleaner combustion characteristics. Several developed nations have already integrated CNG technology in both passenger and commercial vehicles to comply with Euro 6.2 emission standards.

India’s automotive sector has experienced rapid regulatory evolution with the implementation of Bharat Stage (BS 6) norms in 2020 and the subsequent BS 6.2 upgrade in 2023. These regulations impose highly stringent limits on harmful pollutants; achieving compliance requires both improved combustion management and advanced after-treatment systems. CNG engines have developed as a practical way to reduce emissions in metropolitan areas in India.

II. LITERATURE REVIEW.

2.1. Fundamentals of Air–Fuel Ratio (λ).

The Air-Fuel ratio (λ) plays an effective role in determining the combustion characteristics, emission formation, and performance of engines operating on CNG. It is defined as the ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio. In simple expressions, it specifies whether the mixture supplied to the engine is rich, stoichiometric, or lean.

Several studies and researchers use the air-fuel ratio in the perspective of lambda as a primary for studies of combustion control, emissions analysis, and engine efficiency.

The air-fuel ratio lambda value represents the ratio of actual air supplied to the stoichiometric air requirement.

$$\lambda = (A/F)_{actual} / (A/F)_{stoichiometric}$$

Where:

$(F/A)_{actual}$ = actual fuel-to-air ratio supplied to the engine,

$(F/A)_{stoichiometric}$ = stoichiometric fuel-to-air ratio required for ideal combustion.

The accurate control of λ is essential for engine performance, fuel efficiency, and compliance with emission standards like Bharat Stage 6.2 [22].

2.2. Stoichiometric Mixture.

A stoichiometric mixture is one where the exact amount of air is supplied for complete combustion of the fuel, leaving no unburned oxygen or fuel after reaction. For methane (CH_4), which is the main constituent of CNG, the stoichiometric combustion reaction is:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

From this, the stoichiometric air–fuel ratio (A/F) for methane is approximately 17.2:1 by mass, or equivalently $(F/A)_{sto} = 0.0581$.

Table No. 01: Interpretation of Rich, Stoichiometric, and Lean Mixtures

Sr No	Condition	Air-Fuel ratio- Lambda (λ)	Description
1	Rich Mixture	$\lambda < 1$	Excess fuel leads to incomplete combustion, higher CO and THC emissions, and lower NOx.
2	Stoichiometric Mixture	$\lambda = 1$	Ideal air–fuel balance; best TWC efficiency
3	Lean Mixture	$\lambda > 1$	Excess air promotes complete combustion, lowers CO/HC, but increases NOx at moderate levels.

2.3. Effect of λ on Combustion and Emissions

The air-fuel ratio has a major influence on combustion behavior and emission characteristics in CNG engines. When the mixture is rich, more fuel is present than needed for complete combustion. Slightly rich mixtures give maximum power output, while lean mixtures improve fuel economy, as shown in figure no 1, and reduce CO. However, NOx emissions peak near the stoichiometric point due to high combustion temperatures.

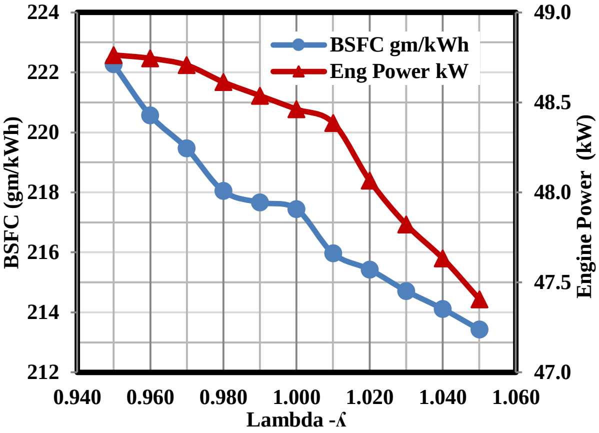

Figure No 1: Lambda Vs Power & BSF

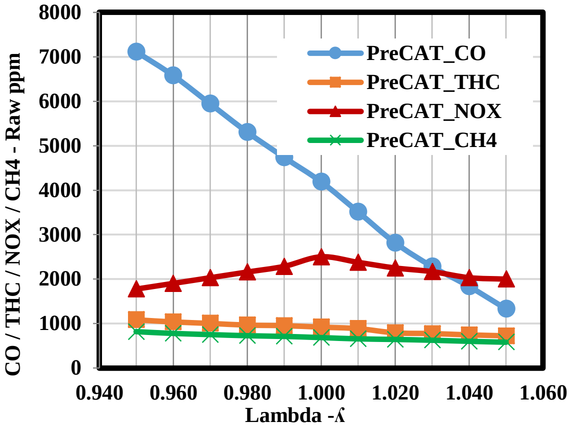

Figure No 2: Lambda Vs Pre-Catalyst Emission

This initially raises the flame temperature but later causes incomplete combustion, resulting in higher CO and THC emissions. Under lean conditions, excess air lowers the flame speed and combustion temperature, improving efficiency but increasing the risk of misfire at very low fuel levels, as shown in figure no 2. Extremely lean mixtures can lead to incomplete combustion and catalyst deactivation. Therefore, maintaining λ close to 1.00 ± 0.02 using ECU-based control is essential to ensure optimum combustion efficiency.

2.4. Three-Way Catalyst Performance.

The TWC reduces CO and HC through oxidation and converts NOx through reduction. Its operation is highly sensitive to λ. Stoichiometric the catalyst's oxygen storage function helps maintain efficiency even with small fluctuations. However, continuous lean or rich operation leads to incomplete conversions, especially for CH_4, and the three-way catalyst simultaneously performs the following reactions:

1) CO oxidation → $CO + \tfrac{1}{2}O_2 \rightarrow CO_2$

2) HC oxidation → $C_xH_y + O_2 \rightarrow CO_2 + H_2O$

3) NOx reduction → $2NO \rightarrow N_2 + O_2$

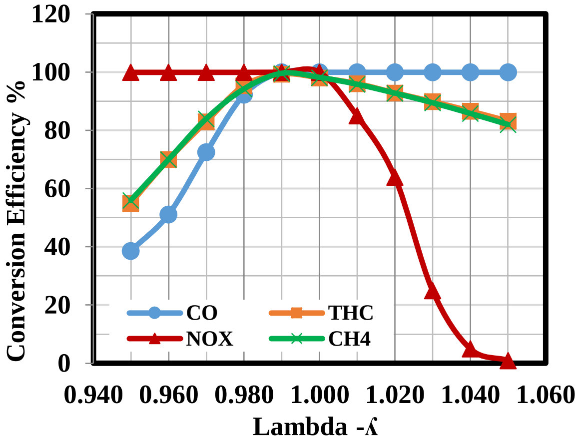

Figure No 3: Lambda Vs Catalyst Conversion Efficiency

The active layer of the TWC consists of noble metals (Pt, Pd, Rh) coated on a high-surface-area ceramic substrate. Pd and Pt favor oxidation of CO and HC, while Rh helps NOx reduction. Conversion efficiency peaks at λ ≈ 1. Even slight deviations (rich or lean) reduce efficiency as shown in figure no 3.

2.5. ECU-Based Lambda Control Strategies.

Accurate lambda controlling and monitoring are essential in multi-cylinder CNG engines to ensure each cylinder operates in the maximum three-way catalyst efficiency zone. The Control strategies include 1) Closed-loop feedback: ECU adjusts fuel trim/injection duration based on oxygen sensor feedback readings.

2) Wideband λ sensors: Provide accurate λ measurement across rich and lean ranges, & 3) λ dithering: Small oscillations around λ = 1 enhance catalyst oxygen storage and conversion stability. Such strategies are supporting to ensure BS 6.2 compliance under real driving conditions.

2.6. Bharat Stage 6.2 Emission Standards [22]

BS 6.2 standards, introduced in India, align closely with Euro VI but include methane-specific regulations due to CNG usage. Limits for passenger vehicles & transport vehicles heavy-duty (HD) SI engines typically above 3.5 tons:

Table No 02: BS 6.2 Emission Standards for Vehicles category M & N > 3.5 tons

Emission	**CO**	**NOx**	**NMHC**	**CH_4**
Unit	mg/kWh	mg/kWh	mg/kWh	mg/kWh
BS 6.2 Limits	4000	460	160	500

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

2.7. Early Studies on Air-Fuel Ratio and Emissions (2000–2010)

Initial studies into the role of the air-fuel ratio on CNG engine emissions, & mainly focused on understanding how variations in the air–fuel mixture influence NOx, CO, and unburned hydrocarbon levels. The work done in the early 2000s laid the foundation for identifying the lean and rich operation limits.

Experimental studies during this period showed that when the air-fuel ratio was reduced below stoichiometric levels, a significant drop in combustion temperature occurred, leading to lower NOx emissions but higher unburned hydrocarbons due to incomplete combustion [1]. This behavior was attributed to the reduced flame propagation speed in lean mixtures, which caused partial oxidation of methane and left traces of unreacted fuel in the exhaust gases. The flame temperature rises sharply, enhancing the formation of thermal NOx through the extended Zeldovich mechanism [2].

Further research explored the combined impact of mixture strength and ignition timing on overall emission characteristics, and tests revealed that maintaining an air-fuel ratio between 0.9 and 1.0 provided the best compromise between power output and emission control [3].

During the same period, the relationship between ʎ and catalytic converter efficiency started to attract attention. Studies showed that three-way catalysts (TWC) performed optimally when the exhaust gas composition was close to stoichiometric, enabling simultaneous oxidation of CO and HC and reduction of NOx [2]. However, under lean-burn conditions, the oxygen concentration in the exhaust increased, reducing the effectiveness of NOx reduction while improving CO and HC oxidation efficiency. This trade-off became an important consideration for engine calibration strategies in the 2000s.

The introduction of lambda (λ) sensors in CNG engines also played a major role in improving fuel control accuracy. By continuously monitoring the oxygen level in the exhaust, these sensors enabled closed-loop air–fuel ratio correction to maintain the desired air-fuel ratio in real-time operation [3]. Early sensor-based systems were, however, limited by slow response times and low precision during transient conditions, especially at high engine speeds and variable loads.

Reasonable emission studies between gasoline and CNG engines discovered that CNG combustion produced substantially lower particulate and soot emissions, mainly due to the absence of heavy hydrocarbons in methane fuel [4]. The results also confirmed that NOx emissions in CNG engines are high.

By the end of this period, researchers had established a clear understanding that lean-burn operation could significantly enhance fuel economy and reduce NOx emissions. However, this approach introduced new challenges such as increased HC and methane slip, as well as reduced TWC effectiveness. These challenges set the stage for subsequent studies in the following decade (2010–2020), where attention shifted towards catalyst optimization, engine control technologies, and real-time air-fuel ratio management for improved emission control [5].

2.8. Advancement in Catalyst and Combustion Control (2010–2020)

The decade from 2010 to 2020 observed a major change in the understanding and control of ʎ effects on CNG engines. The focus gradually moved from purely combustion analysis toward integrated systems combining fuel-air management, catalytic after-treatment, and real-time feedback devices. These developments were motivated by the tightening of worldwide emission regulations such as Euro 6 and India’s BS VI norms, which demanded simultaneous reductions in NOx, CO, and unburned methane without compromising performance.

Studies in this period emphasized that small deviations in the air-fuel ratio could cause significant variations in emission behavior by over 15%, depending on the engine operating conditions [3]. Researchers confirmed that CNG engines achieved their cleanest operation near stoichiometric conditions, as this allowed the three-way catalyst (TWC) to maintain its optimal conversion efficiency for all major pollutants [4].

However, keeping the air-fuel ratio at stoichiometry was not straightforward, especially under transient engine operation or variable ambient conditions. Advanced ECU-based systems were thus developed to continuously adjust the injection pulse width and ignition phase based on the measured lambda value [5]. These systems improved response accuracy and significantly improved the stability of combustion under both lean and stoichiometric operations.

In parallel, research into catalyst technology made considerable progress. Studies reported that the conversion efficiency of TWCs depends on the air-fuel ratio window. When ʎ range 0.9 to 1.01, the TWC achieved over 95% conversion efficiency for NOx and CO simultaneously [6].

Further work examined the light-off characteristics of catalysts under different mixture strengths. It was found that leaner mixtures delayed catalyst light-off due to reduced exhaust temperatures, while richer mixtures accelerated activation but risked incomplete oxidation of CO [4]. Therefore, balancing the air-fuel ratio during cold-start conditions became an important area of optimization for meeting low-temperature emission requirements.

Lean-burn operation was another focus area during this decade. Even if it improved fuel economy and reduced CO_2 emissions, lean operation introduced the problem of methane slip, unburned methane that escapes into the exhaust without oxidation. Researchers quantified that methane slip could contribute up to 20% of total hydrocarbon emissions during lean operation [7]. As methane has a high global warming potential, minimizing its emission has become a critical environmental objective.

To tackle this, new catalyst formulations with enhanced oxygen storage capacity and improved methane oxidation activity were introduced. For example, Pd-based catalysts demonstrated better performance for methane oxidation at lean conditions compared to traditional Pt-Rh systems [8]. These catalysts were often combined with advanced thermal management strategies, such as pre-heating exhaust streams or using electrically heated catalysts, to achieve earlier light-off and reduce cold-start methane slip.

In addition to hardware improvements, several researchers explored the role of real-time adaptive control algorithms in maintaining the desired air-fuel ratio. These algorithms used input data from manifold pressure, intake temperature, and oxygen sensors to dynamically predict and adjust the required fuel quantity [9].

By 2020, the researchers had achieved a deeper understanding of how air-fuel ratio control influences the entire emissions control system. The combined use of closed-loop lambda feedback, optimized catalyst compositions, and improved ECU calibration provided a strong groundwork for the next stage of development, full compliance with BS VI and Euro 6.2 regulations for multi-cylinder CNG engines under real-world driving conditions [10].

2.9. Modern Developments under BS VI and Euro 6.2 (2020–2025)

Through the introduction of BS 6.2 emission norms, the focus of research on CNG engines shifted toward achieving ultra-low emissions under both laboratory and real driving conditions. For this, the role of ʎ control became more significant because it directly affected emissions of NOx, CO, and unburned methane (CH_4) across diverse operating conditions [11].

During this phase, researchers highlighted the need for steady-state air-fuel ratio mapping to accurately characterize the emission response. Such mapping identifies regions where stoichiometric operation ensured maximum catalyst efficiency and where lean or rich operation offered trade-offs in fuel economy or power [11].

The introduction of real driving emission (RDE) testing highlighted the limitations of traditional calibration methods. To address this, adaptive control systems using closed-loop lambda feedback and predictive algorithms were employed to continuously adjust the air–fuel mixture [12].

Researchers explored the use of enhanced three-way catalysts (TWCs) with improved Pd–Pt formulations capable of lowering the methane light-off temperature by nearly 50°C [18]. These formulations achieved better conversion efficiency in the ʎ range of 0.97–1.03, where stoichiometric oscillations promoted oxygen storage and release cycles beneficial for complete oxidation [18].

By pre-heating the exhaust or using electrically assisted catalysts, researchers managed to achieve up to 90% methane conversion during cold-start phases [14]. This progress was complemented by studies on catalyst aging, which revealed that prolonged exposure to thermal cycling could alter the oxygen storage characteristics of the washcoat material and shift the effective air-fuel ratio window [14].

Parallel significant improvements were made in engine control unit (ECU) strategies. Research showed that machine learning-assisted calibration could identify optimal air-fuel ratio set points across varying environmental conditions, such as humidity, altitude, and temperature [20]. As a result, machine learning approaches improved transient stability and reduced both fuel consumption and emission inconsistency compared to traditional PID-based control [20].

These adaptive systems continuously fine-tune the mixture strength based on instantaneous readings from multiple lambda sensors located upstream and downstream of the TWC [13]. Such real-time adjustments ensured that the exhaust composition remained within the ideal stoichiometric window, maximizing the TWC efficiency for NOx, CO, and CH_4 simultaneously.

Furthermore, the development of advanced emission measurement techniques using Fourier-transform infrared (FTIR) analyzers and constant volume sampling (CVS) systems provided highly accurate data on transient emission behavior [15]. These tools enabled engineers to construct detailed emission maps showing the variation of pollutants with air-fuel ratio, load, and temperature.

A combined modeling framework was later proposed to couple air-fuel ratio control, after-treatment modeling, and compliance evaluation under BS 6.2 regulations [16], [21]. This structure considered catalyst efficiency degradation, transient heat transfer, and lambda sensor dynamics, enabling predictive assessment of vehicle compliance over extended in-service durations. Studies applying this model found that air-fuel ratio fluctuations during real driving were the dominant cause of methane and NOx exceedances [17].

Researchers reported that several production vehicles initially meeting laboratory emission limits showed emissions exceeding thresholds during ISC due to control drift and sensor aging [17]. The findings highlighted the importance of robust calibration protocols that could adapt to long-term changes in engine and catalyst behavior.

Recent studies extended these concepts by incorporating multi-cylinder synchronization, where air-fuel ratio deviations among cylinders were individually corrected using cylinder-specific lambda sensors [19]. This technology significantly reduced inter-cylinder variation and improved catalyst inlet uniformity, leading to lower NOx and methane emissions.

Overall, the period from 2020 to 2025 established that effective air-fuel ratio management in CNG engines requires a synergistic approach combining advanced ECU control, optimized catalyst design, machine learning-based predictive systems, and accurate emission measurement protocols. Together, these technologies have enabled near-zero emission operation of CNG spark-ignition engines under the most stringent regulatory frameworks [20], [21].

III. IDENTIFIED RESEARCH GAP.

1. Most prior studies focused on single-cylinder or simulation-based models, lacking validation on multi-cylinder CNG engines under BS 6.2 norms.

2. There is no standardized λ sweep or steady-state test protocol for BS 6.2 multi-cylinder CNG engines.

3. Adaptive and machine-learning-based ECU calibration strategies lack experimental validation using physical emission data.

4. Existing works do not integrate combustion, catalyst, and ECU control analysis, leading to an uneven understanding of overall emission control behavior.

5. No comprehensive steady-state air-fuel ratio (λ) mapping datasets are available for BS 6.2-compliant CNG engines using FTIR, HFID, and CVS-grade instruments.

6. Methane slip mechanisms and temperature dependence remain insufficiently studied, especially

under cold start and transient operations.

7. Long-term catalyst aging effects on light-off and conversion efficiency are rarely analyzed experimentally.

8. The link between steady-state λ calibration and real-world ISC (In-Service Conformity) emissions has not been clearly established.

9. Catalyst formulation–λ interaction, particularly for Pd/Pt/Rh compositions, is not experimentally correlated with ECU λ control strategies.

10. The influence of regional variations in natural gas composition on air-fuel ratio and emission behaviour remains unexplored.

Hence, this review aims to systematically evaluate λ variation in a multi-cylinder BS 6.2-compliant CNG engine, using steady-state λ sweeps to map combustion characteristics, tailpipe emissions, and catalyst efficiency. The outcomes will help in developing robust calibration strategies, ensuring both regulatory compliance and engine performance optimization.

IV. PROBLEM DEFINITION.

Existing research does not provide an integrated experimental structure linking air-fuel ratio variation, catalyst performance, and ECU calibration under BS 6.2 emission norms. Prior studies focus on isolated systems, without synchronized pre- and post-catalyst emission data or validation of adaptive control strategies. Therefore, the fundamental research problem is to determine the optimal equivalence-ratio control strategy and catalyst operating window that minimizes NOx, CO, and CH_4 emissions while maintaining BS 6.2 compliance across steady-state conditions.

V. CONCLUSION.

Air–fuel ratio (λ) control remains a fundamental parameter governing combustion behavior, emission formation, and catalyst performance in CNG spark ignition engines. The review indicates that even minor deviations from stoichiometric conditions significantly influence NOx, CO, and hydrocarbon emissions.

Over the past two decades, advancements in engine performance, catalyst technology, ECU calibration, and emission measurement systems have significantly improved emission control competencies. However, challenges such as methane slip, catalyst aging, and transient λ instability remain unresolved. Future research must focus on integrated combustion–catalyst–control systems validated under multi-cylinder BS 6.2 operating conditions to achieve robust real-world emission compliance.

Even if several Indian researchers and their studies have examined these effects, & few have done so under BS 6.2 emission-compliant conditions or using multi-cylinder engines equipped with modern ECU-based fuel systems. Hereafter, there remains a lack of comprehensive data integrating combustion behavior and catalyst performance under real Indian test conditions. Future research should focus on integrated combustion–catalyst–ECU frameworks, supported by multi-cylinder experimental validation and real-time adaptive control strategies, to ensure robust compliance with BS6.2 emission norms.

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