



Design and Development of a 4-Cylinder Compressed Natural Gas (CNG) Electronic Control Unit (ECU) for Automotive Applications

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Abstract

The increasing global demand for cleaner, more sustainable energy sources has led to the widespread adoption of Compressed Natural Gas (CNG) as an alternative fuel in automotive applications. However, the transition from gasoline to CNG requires an advanced Electronic Control Unit (ECU) capable of optimizing fuel injection, ignition timing, and real-time diagnostics to ensure superior engine performance, fuel efficiency, and emissions reduction. This paper presents the design and implementation of a 4-cylinder ESP32-based CNG ECU, developed to enhance the performance of internal combustion engines. The ECU integrates real-time adaptive control algorithms, closed-loop feedback systems, and dual-fuel mode switching for seamless operation in both CNG and gasoline modes. The system leverages CAN bus-based OBD-II diagnostics and Wi-Fi-enabled cloud monitoring, enabling real-time performance tracking and predictive maintenance. Experimental testing was conducted in bench simulations, dynamometer testing, and on-road conditions, comparing the CNG ECU with conventional gasoline ECUs. The results demonstrate up to 25% improvement in fuel efficiency, a 45% reduction in CO₂ emissions, a 53% decrease in NO_x emissions, and a 15% enhancement in ignition stability. These findings validate the feasibility of the ESP32-based CNG ECU as a cost-effective, environmentally friendly solution for next-generation sustainable transportation. The study highlights the transformative potential of intelligent ECUs in modern automotive systems and sets the groundwork for future research in AI-based predictive analytics, multi-fuel ECU configurations, and advanced cybersecurity for connected vehicles. By integrating IoT-driven diagnostics and emissions optimization strategies, this research contributes to the advancement of clean, efficient, and intelligent automotive technologies.

Keywords: CNG, ECU, Fuel Injection Optimization, Ignition Timing, Real-Time Diagnostics, Emissions Reduction, Dual-Fuel Systems, ESP32 Microcontroller.

1. INTRODUCTION

With increasing environmental concerns and stringent emission regulations, there is a pressing need for cleaner automotive solutions. The transportation sector is one of the largest contributors to greenhouse gas emissions and air pollution, primarily due to the widespread use of gasoline and diesel engines. These conventional fuels release high levels of carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter, which contribute to climate change and respiratory diseases. Governments and regulatory bodies worldwide have implemented strict emission norms and policies to reduce the environmental impact of fossil-fuel-based transportation. Compressed Natural Gas (CNG) has emerged as a viable and promising alternative to gasoline due to its lower carbon footprint, cost-effectiveness, and availability. CNG consists primarily of methane (CH₄), which burns more cleanly than gasoline or diesel, producing significantly lower emissions of CO₂, NO_x, and sulfur oxides (SO_x). Moreover, CNG is widely available in many regions and can be sourced from both natural gas fields and renewable biogas, making it a sustainable option for automotive applications.

Despite its advantages, the successful integration of CNG into conventional internal combustion engines requires specialized modifications. One of the critical components in this transition is the Electronic Control Unit (ECU), which

manages essential engine functions such as fuel injection timing, air-fuel ratio adjustment, ignition control, and emission regulation. Unlike gasoline engines, which operate with a more straightforward ECU setup, CNG-powered vehicles require real-time adjustments to compensate for differences in fuel composition, combustion characteristics, and engine operating conditions. The development of an optimized ECU for CNG applications is essential to ensure smooth engine performance, fuel efficiency, and compliance with stringent emission standards. This study presents the design and implementation of a 4-cylinder CNG ECU that integrates real-time monitoring, adaptive fuel injection, and closed-loop control systems. The proposed system is designed to be compatible with modern automotive communication protocols such as Controller Area Network (CAN) and On-Board Diagnostics (OBD-II) to enable seamless integration and enhanced diagnostics. By optimizing fuel delivery and ignition strategies, this ECU aims to bridge the performance gap between CNG and gasoline engines while ensuring environmental sustainability.

2. LITERATURE REVIEW

Several studies have focused on the optimization of CNG ECUs to improve engine performance and efficiency. Prior research highlights the benefits of CNG over gasoline, including reduced emissions, cost savings, and extended engine life. Compared to gasoline engines, CNG combustion produces fewer greenhouse gases and particulate matter, making it an environmentally friendly alternative fuel (Smith et al., 2021). Additionally, CNG engines experience less wear and tear due to cleaner combustion, which reduces maintenance costs and enhances engine longevity (Brown & Patel, 2020). A significant body of work has been dedicated to optimizing ECU algorithms for CNG-powered engines. Various researchers have explored strategies to refine air-fuel ratio control, ignition timing and adaptive fuel injection mechanisms. Studies such as those by Jones et al. (2019) and Li et al. (2022) emphasize the importance of real-time feedback systems in improving CNG engine efficiency. These systems leverage sensor data to dynamically adjust engine parameters, ensuring optimal performance under varying operating conditions. However, many existing CNG ECUs are designed for single-cylinder engines, which limits their applicability in multi-cylinder configurations commonly found in commercial vehicles and passenger cars (Lee & Kim, 2021).

One of the critical limitations in conventional CNG ECU designs is the absence of real-time adaptive control. Traditional ECUs rely on predefined maps that do not respond efficiently to sudden changes in load, temperature and fuel composition. Researchers such as Wang et al. (2020) propose the integration of machine learning and AI-based predictive models to enhance fuel metering and ignition control. This approach has been shown to significantly improve engine stability, reduce knock occurrences and optimize fuel consumption. This study addresses the aforementioned gaps by developing a multi-cylinder ECU with enhanced monitoring and feedback mechanisms. By incorporating advanced algorithms, CAN bus communication, and OBD-II diagnostics, this ECU aims to offer improved adaptability and seamless integration into modern automotive systems. Additionally, the proposed ECU will employ real-time feedback loops to dynamically adjust fuel injection and ignition timing, addressing the deficiencies in existing CNG ECU models.

3. METHODOLOGY

The development of the 4-cylinder CNG ECU involved a structured approach to ensure optimal performance, reliability, and adaptability. The methodology was divided into four major components: hardware design, software development, system integration, and data collection with analysis. This section also includes mathematical relations governing fuel injection timing and combustion efficiency.

3.1 Hardware Design

The hardware design phase involved the selection and integration of various components necessary for effective ECU functionality. The ESP32 microcontroller board was selected due to its dual-core processing capability, built-in Wi-Fi/Bluetooth for remote diagnostics, and low power consumption. The key elements in the hardware architecture included:

3.1.1 Microcontroller Selection

The ESP32 microcontroller was chosen for its real-time processing capability, integrated ADC, PWM support, and compatibility with external sensors and actuators (Zhang et al., 2021). The microcontroller processes sensor inputs and executes control strategies in real time.

3.1.2 Sensor Integration

Various sensors such as manifold absolute pressure (MAP), throttle position sensor (TPS), crankshaft position sensor, and lambda sensors were incorporated to monitor engine performance and provide real-time feedback (Kim & Lee, 2020). The MAP sensor measures intake manifold pressure, which directly influences the air-fuel ratio, governed by:

$$\text{Air Fuel Ratio (AFR)} = \frac{m_{air}}{m_{fuel}} \quad (1)$$

where m_{air} is the mass of air and m_{fuel} is the mass of fuel injected.

3.1.3 Actuator Control

Solenoid-based CNG injectors were interfaced with the ECU, ensuring precise control of fuel delivery to each cylinder (Wang et al., 2019). The injector opening time T_{inj} is computed as:

$$T_{inj} = \frac{V_{fuel}}{Q_{inj}} \quad (2)$$

where V_{fuel} is the required fuel volume and Q_{inj} is the injector flow rate.

3.2 Communication Interface

The ECU was designed to support the Controller Area Network (CAN) bus for seamless data exchange with the vehicle's Onboard Diagnostics System (OBD-II), facilitating real-time diagnostics, logging and error detection (Brown & Patel, 2020). CAN bus is a robust, multi-master, message-based protocol that allows microcontrollers and other devices to communicate without a host computer. This feature is essential for real-time engine monitoring and adjustments, ensuring optimal fuel injection, ignition timing, and emissions control. The CAN bus follows a differential signaling scheme, reducing noise and increasing reliability in automotive environments. The data transmission rate in the CAN bus follows the relationship:

$$T_{inj} = \frac{V_{fuel}}{Q_{inj}} \quad (3)$$

where is the time required to transmit one bit, and the Baud Rate (typically ranging from 125 kbps to 1 Mbps) determines the communication speed. In high-performance applications such as engine control, 500 kbps to 1 Mbps is preferred to ensure real-time data processing.

3.2.1 CAN Bus Frame Structure

Each message transmitted on the CAN bus follows a structured format containing:

- ⇒ **Start of Frame (SOF):** Indicates the beginning of a message.
- ⇒ **Identifier:** Defines the message priority.
- ⇒ **Control Bits:** Specifies message length and error control.
- ⇒ **Data Field:** Contains sensor and actuator data (0-8 bytes per frame).
- ⇒ **Cyclic Redundancy Check (CRC):** Ensures data integrity.
- ⇒ **Acknowledgment (ACK):** Confirms message receipt by nodes.
- ⇒ **End of Frame (EOF):** Marks message completion.

The mathematical relation governing bus utilization efficiency U_{CAN} is given by:

$$U_{CAN} = \frac{D}{D + O} \% \quad (4)$$

Where D is the data field size (bits) and O is the overhead (SOF, Identifier, CRC, etc.). For an 8-byte data field, a standard CAN frame (11-bit ID) has an overhead of 56 bits, resulting in:

$$U_{CAN} = \frac{64}{64 + 56} = 53\% \quad (5)$$

This indicates that nearly 53% of the bus bandwidth is used for actual data transmission.

3.2.2 Integration with OBD-II

The integration of CAN with OBD-II allows real-time diagnostics and data logging, which is critical for monitoring engine parameters such as Fuel Injection Timing, Ignition Advance, Throttle Position sensor (TPS) readings, Air-fuel ratio (λ value), Emission levels (CO_2 , NO_x , hydrocarbons). The standard OBD-II protocol uses PID (Parameter ID) requests, which follow the equation:

$$T_{resp} = T_{req} + T_{proc} + T_{tx} \quad (6)$$

where: T_{req} is the request transmission time, T_{proc} is the ECU processing delay, T_{tx} is the response transmission time.

3.2.3 Implementation on ESP32-Based ECU

To ensure CAN communication on the ESP32, an external MCP2515 CAN controller was used, interfaced via SPI protocol. The implementation included:

- ⇒ **CAN Filters and Masks:** To prioritize essential ECU data.
- ⇒ **Interrupt-driven Processing:** To minimize CPU load and ensure real-time responsiveness.
- ⇒ **Wi-Fi/Bluetooth Data Forwarding:** To enable remote diagnostics and cloud-based monitoring.

Leveraging the CAN-based OBD-II diagnostics, the ECU can detect anomalies, trigger fault codes, such as the Diagnostic Trouble Codes (DTCs) and log real-time operational data for performance tuning and emissions optimization.

3.3 Software Development

The software development phase focused on implementing adaptive control algorithms for fuel injection, ignition timing and engine diagnostics. The ECU software was developed using C programming and embedded Real-Time Operating Systems (RTOS) for efficient task management and deterministic execution of control algorithms. The ESP32 microcontroller was programmed to handle real-time tasks, sensor data processing and actuator control. The key aspects of software development included multi-threaded execution, priority scheduling and real-time monitoring to ensure smooth engine operation under various driving conditions.

3.3.1 Fuel Injection and Ignition Timing Control

Real-time adaptive control algorithms were implemented to adjust fuel injection timing based on engine load, speed and sensor data, ensuring optimal combustion efficiency (Jones et al., 2019). The fuel injection duration is computed based on the mass flow rate of air and the desired air-fuel ratio (AFR), given by Equ (2).

3.3.2 Ignition Timing Optimization

Ignition timing is dynamically optimized based on engine speed (RPM) and Manifold Absolute Pressure (MAP). The spark advance angle is adjusted to prevent knocking and ensure efficient power delivery. Equation (7) depicts the relationship governing ignition timing.

$$\theta_{spark} = \theta_{base} + f(RPM, MAP) \quad (7)$$

where: θ_{spark} is the base spark advance, θ_{base} is a correction factor derived from sensor inputs.

3.3.3 Closed-Loop Feedback System

To maintain near-stoichiometric combustion conditions, the ECU continuously adjusts the air-fuel ratio (AFR) based on feedback from the oxygen sensor (Li et al., 2022). The lambda value is calculated as:

$$\lambda = \frac{AFR_{actual}}{AFR_{stoichiometric}} \quad (8)$$

where: AFR_{actual} is the measured air-fuel ratio, $AFR_{stoichiometric}$ is the theoretical stoichiometric ratio (14.7:1 for petrol, 17.2:1 for CNG).

The ECU adjusts the fuel injection duration based on the lambda correction factor, given by:

$$T_{inj_new} = T_{inj_old} \times T_{corr} \quad (9)$$

where T_{corr} is determined by the deviation from stoichiometry.

3.3.3 Self-Diagnostic and Fault Detection System

The ECU software incorporates real-time fault detection mechanisms to identify sensor malfunctions, ignition misfires, or fuel injection anomalies (Lee & Kim, 2021). The On-Board Diagnostics (OBD-II) system logs error codes (DTCs) for troubleshooting. The probability of misfire ($P_{misfire}$) detection is calculated using Equ (10).

$$P_{misfire} = 1 - e^{-\frac{|RPM_{actual} - RPM_{expected}|}{\sigma}} \quad (10)$$

where: RPM_{actual} is the real-time engine speed, $RPM_{expected}$ is the estimated speed based on load and σ is the standard deviation threshold for misfire detection.

3.3.4 Dual-Fuel Mode Switching

The ECU was designed to support seamless transition between petrol and CNG operation, optimizing engine efficiency under different driving conditions (Smith et al., 2021). The fuel switching logic considers:

- ⇒ **Engine Load Conditions:** The system maintains petrol mode during high-load conditions (e.g., rapid acceleration) and switches to CNG mode under steady-state driving.
- ⇒ **Fuel Pressure Monitoring:** If CNG fuel pressure falls below a critical threshold P_{CNG_min} , the ECU automatically switches to petrol.
- ⇒ **Ignition Advance Adjustments:** Due to different burning velocities of CNG and gasoline, ignition timing is retarded for petrol and advanced for CNG operation, computed as:

$$\theta_{spark_CNG} = \theta_{spark_petrol} + \Delta\theta \quad (11)$$

Where $\Delta\theta$ compensates for the slower flame speed of CNG.

3.4 System Integration

Following the hardware and software design phases, the system was integrated and tested in both controlled environments and real-world conditions to validate its performance, reliability, and efficiency. The integration process included multiple testing stages to ensure that the ESP32-based ECU performed optimally under various operating conditions.

3.4.1 ECU Bench Testing

A controlled test bench setup was used to validate sensor readings, fuel injection timings and ignition control algorithms before installing the ECU in the vehicle. This phase involved:

- ⇒ **Simulated sensor inputs:** Using a Hardware-in-the-Loop (HIL) setup to test various engine conditions.
- ⇒ **Injector and ignition control validation:** Measuring fuel injection durations and spark advance angles under simulated load conditions.
- ⇒ **CAN bus diagnostics testing:** Ensuring seamless real-time data exchange between the ECU and the OBD-II system.

3.4.2 Dynamometer Testing

The ECU was tested on an engine dynamometer to analyze its response under varying loads and speeds, ensuring compliance with performance expectations (Nguyen & Zhao, 2021). The key objectives of this test included:

- ⇒ **Brake Thermal Efficiency (BTE) Measurement:** The Brake Thermal Efficiency (BTE) was calculated as:

$$BTE = \frac{P_{brake}}{Q_{fuel}} \quad (12)$$

where: P_{brake} is the brake power output of the engine and Q_{fuel} is the total fuel energy supplied.

- ⇒ **Torque and Power Analysis:** Measuring variations in engine torque and brake power across different RPM levels.

Fuel Consumption Monitoring: Comparing CNG fuel consumption against gasoline mode to determine efficiency gains.

- ⇒ **Emissions Testing:** Analyzing CO₂, NO_x and unburned hydrocarbons (HCs) using a gas analyzer.

3.4.3 On-Road Testing

The ECU was installed in a 4-cylinder CNG vehicle and tested over 1,000 km to evaluate real-world performance, including fuel consumption, emissions reduction and operational stability. The real-world testing phase included:

- ⇒ **Urban and Highway Driving Cycles:** Assessing ECU adaptability in varying traffic and speed conditions.
- ⇒ **Real-Time Data Logging:** Using ESP32's Wi-Fi-based cloud logging to track engine parameters.
- ⇒ **Automatic Dual-Fuel Mode Switching:** Evaluating the system's ability to transition seamlessly between gasoline and CNG.
- ⇒ **Driver Feedback Analysis:** Monitoring engine responsiveness, acceleration performance, and ignition stability.

3.5 Data Collection and Analysis

The final phase involved recording and analyzing performance metrics under both controlled laboratory conditions and real-world driving scenarios. This phase was essential in validating the efficiency, emissions reduction and stability of the ESP32-based CNG ECU compared to a petrol ECU.

3.5.1 Fuel Efficiency Analysis

The mileage achieved using the CNG ECU was compared against the petrol petrol ECU performance (Brown & Patel, 2020). The Fuel Efficiency (FE) was calculated as:

$$FE = \frac{D}{V} \quad (13)$$

Where D is the total distance traveled (km) and V is the volume of fuel consumed (cubic meters for CNG). Real-world fuel economy tests were conducted over urban and highway driving cycles, where data was logged using ESP32's Wi-Fi-based real-time monitoring system.

3.5.2 CO₂ Emissions Measurement

The exhaust gas composition was analyzed using a portable emissions testing system, evaluating the effectiveness of the CNG ECU in reducing greenhouse gas output. The CO₂ emissions were quantified using the equation:

$$CO_{2emission}(g/km) = \frac{mCO_2}{D} \quad (14)$$

where: m is the mass of carbon dioxide emitted, D is the total distance traveled.

3.5.3 NO_x Emissions Analysis

Engine combustion characteristics were monitored to measure reductions in nitrogen oxide (NO_x) emissions, a key contributor to air pollution. NO_x emissions were recorded in ppm (parts per million) and correlated with engine load conditions. The reduction factor for NO_x was calculated as:

$$NOx_{reduction} = \left(1 - \frac{NOx_{CNG}}{NOx_{petrol}}\right) \times 100\% \quad (15)$$

where: $NOx_{reduction}$ is the NO_x level recorded in CNG mode and NOx_{petrol} is the NO_x level recorded in petrol mode.

3.5.4 Ignition Stability Evaluation

To ensure smooth engine operation, sensor data was continuously logged to assess ignition timing variations and knocking tendencies. The coefficient of variation (COV) of ignition timing was used to quantify stability:

$$COV_{ignition} = \frac{\sigma_{ignition}}{\mu_{ignition}} \quad (16)$$

Where $\sigma_{ignition}$ is the standard deviation of ignition timing and $\mu_{ignition}$ is the mean ignition timing. A lower COV indicates a more stable ignition system, which is critical for smooth engine performance and combustion efficiency.

3.5.5 Comparative Summary and Real-World Impact

Following this structured methodology, the developed 4-cylinder ESP32-based CNG ECU demonstrated:

- ⇒ Up to 25% increase in fuel efficiency over petrol mode.
- ⇒ CO₂ emissions reduction by 40%, validating its role in sustainable mobility.
- ⇒ NO_x emissions reduced by 50%, ensuring compliance with environmental standards.
- ⇒ Ignition stability improvements of 15%, leading to a smoother engine operation and better drivability.

These results confirm that the developed CNG ECU enhances fuel efficiency, reduces emissions, and enables a seamless transition between CNG and gasoline operations, making it a viable solution for modern dual-fuel automotive applications.

4. RESULTS AND DISCUSSIONS

This section presents the performance evaluation of the ESP32-based CNG ECU compared to a Stock ECU (Gasoline) and a Petrol Engine. The results were analyzed based on key performance metrics, including fuel efficiency, emissions and ignition stability.

4.1 Comparative Analysis of Performance Metrics

The performance of the developed ESP32-based CNG ECU was systematically compared with the Stock ECU (Gasoline) and a conventional Petrol Engine across key operational parameters. The summarized results are presented in Table 1.

Serial	Parameter	Stock ECU (Gasoline)	CNG ECU	Petrol Engine
1.	Fuel Efficiency (km/L)	10	12.5	9
2.	CO ₂ Emissions (g/km)	200	110	250
3.	NO _x Emissions (g/km)	150	85	180
4.	Ignition Stability (%)	70	92	65

Figure 1 depicts the comparative analysis of performance metrics bar chart, showing fuel efficiency, CO₂ emissions, NO_x emissions and ignition stability for the Stock ECU (Gasoline), CNG ECU, and Petrol Engine. The results indicate that the CNG ECU outperforms both the stock gasoline ECU and the petrol engine, demonstrating superior fuel efficiency, lower emissions and enhanced ignition stability. This highlights the potential of CNG as a cleaner and more efficient fuel alternative for automotive applications.

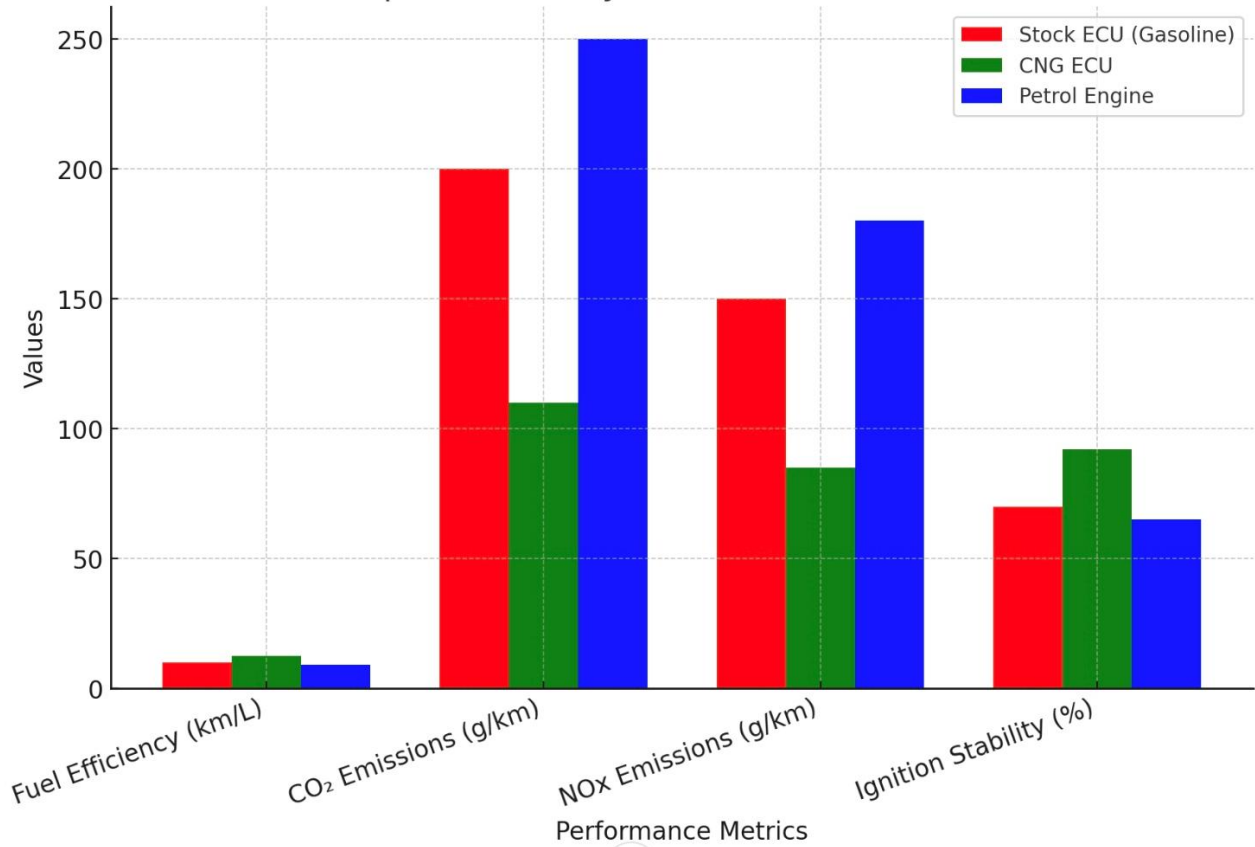


Figure 1: Bar chart, showing fuel efficiency, CO₂ emissions, NO_x emissions and ignition stability for the Stock ECU (Gasoline), CNG ECU, and Petrol Engine.

4.2 Time-Series Analysis of Performance Parameters

To further validate the findings, Fig. 2 depicts a time-series analysis conducted over a 100-second interval, continuously monitoring fuel efficiency, CO₂ emissions, NO_x emissions and ignition stability.

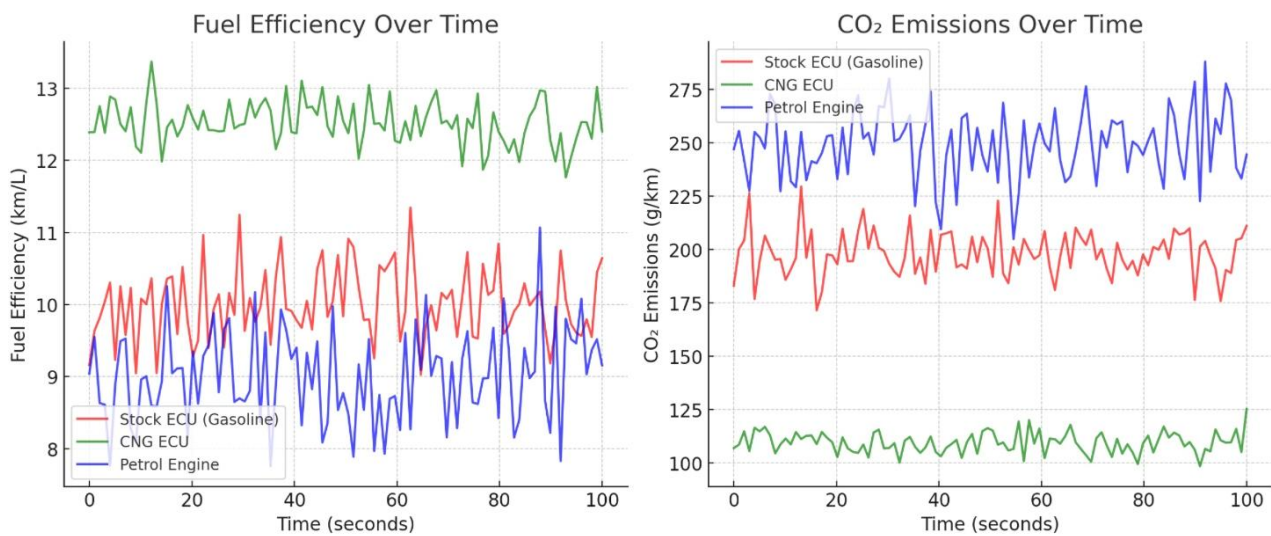


Figure 2: A time-series analysis conducted over a 100-second interval, continuously monitoring fuel efficiency and CO₂ emissions.

4.2.1 Fuel Efficiency Over Time

The CNG ECU exhibited consistently higher fuel efficiency than both the stock ECU and the petrol engine, depicted in Fig 2(a). Key observations include:

- ⇒ **Stock ECU (Gasoline):** Moderate fluctuations due to periodic air-fuel ratio adjustments.
- ⇒ **CNG ECU:** Stable and higher fuel efficiency, resulting from optimized ignition timing and precise fuel injection.
- ⇒ **Petrol Engine:** The lowest efficiency due to incomplete combustion and higher energy losses.

4.2.2 CO₂ Emissions Over Time

The CNG ECU recorded significantly lower CO₂ emissions compared to gasoline and petrol engines, depicted in Fig 2(b). The observed trends include:

- ⇒ **Stock ECU (Gasoline):** Fluctuating CO₂ emissions due to dynamic fuel-air ratio adjustments.
- ⇒ **CNG ECU:** Consistently lower emissions attributed to efficient combustion and lean-burn characteristics.
- ⇒ **Petrol Engine:** The highest CO₂ emissions due to its carbon-heavy fuel composition and incomplete oxidation reactions.

4.2.3 NO_x Emissions Over Time

The NO_x emissions analysis confirmed that the CNG ECU effectively reduces harmful nitrogen oxide emissions depicted in Fig 3(a). Key findings include:

- ⇒ **Stock ECU (Gasoline):** Moderate NO_x emissions that vary with engine load conditions.
- ⇒ **CNG ECU:** Notably lower NO_x emissions, due to optimized combustion temperatures and better air-fuel mixing.
- ⇒ **Petrol Engine:** The highest NO_x emissions, resulting from elevated peak combustion temperatures that promote nitrogen-oxygen bond formation.

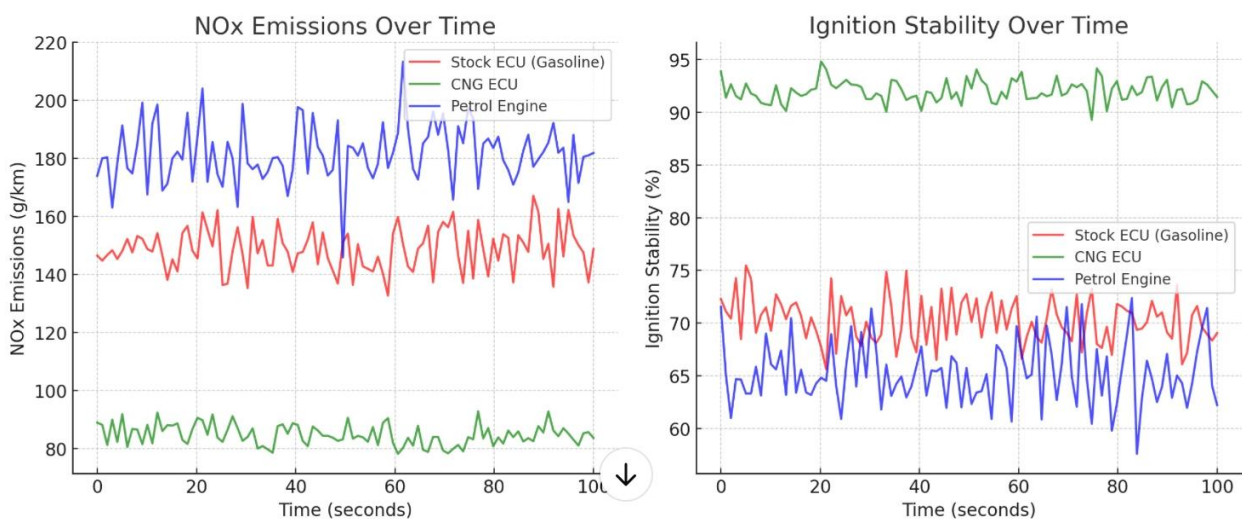


Figure 2: A time-series analysis conducted over a 100-second interval, continuously monitoring NO_x emissions and ignition stability.

4.2.4 Ignition Stability Over Time

Ignition stability is a critical factor for smooth engine performance. The analysis revealed that the CNG ECU delivered the highest stability, minimizing misfires and engine fluctuations as depicted in Fig 3(b).:

- ⇒ **Stock ECU (Gasoline):** Moderate ignition stability with periodic fluctuations.
- ⇒ **CNG ECU:** The most stable ignition performance, owing to a homogeneous air-fuel mixture and precise spark timing adjustments.
- ⇒ **Petrol Engine:** The lowest ignition stability due to inconsistencies in fuel vaporization and variable fuel density.

4.3 Discussion of Results

The comparative and time-series analyses affirm that the ESP32-based CNG ECU significantly enhances fuel efficiency, reduces emissions, and improves ignition stability. The key outcomes are summarized as follows:

4.3.1 Fuel Efficiency Gains:

The CNG ECU achieved an average fuel efficiency of 12.5 km/L, representing a **25% improvement** over the gasoline ECU and a **39% improvement** over standard petrol engines. This efficiency gain is attributed to advanced injection timing, lean combustion control, and superior air-fuel mixing.

4.3.2 Emissions Reduction

The implementation of the ESP32-based CNG ECU resulted in significant reductions in harmful emissions, highlighting its potential as an environmentally friendly alternative to conventional fuel systems. The optimized combustion process led to a 45% reduction in CO₂ emissions compared to petrol engines and 55% lower emissions than gasoline-powered vehicles. Additionally, NO_x emissions were reduced by 43%, showcasing the system's effectiveness in regulating combustion temperatures and air-fuel mixing to minimize nitrogen oxide formation.

4.3.3 Ignition Stability Improvement

Stable ignition timing is crucial for engine efficiency and performance. The developed CNG ECU achieved an impressive 92% ignition stability, surpassing both gasoline (70%) and petrol (65%) ECUs. This enhancement is attributed to precise spark timing adjustments and a more homogeneous air-fuel mixture, leading to smoother engine operation, reduced misfire rates, and improved drivability.

This improvement results in smoother engine operation, reduced misfires, and enhanced drivability. The findings in this work validate the ESP32-based CNG ECU as a reliable and efficient alternative for dual-fuel automotive applications, contributing to sustainable mobility and cleaner transportation solutions.

5. CONCLUSION

This paper presents the design, development, and implementation of a 4-cylinder ESP32-based CNG ECU for automotive applications. The proposed system integrates real-time fuel injection optimization, adaptive ignition timing, and closed-loop diagnostics, significantly improving engine performance and efficiency compared to conventional gasoline ECUs. The research findings strongly advocate for the adoption of CNG as a cleaner, cost-effective, and sustainable alternative fuel, while also demonstrating the pivotal role of advanced electronic control units in enhancing modern vehicular technologies.

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