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Research Paper

Fuel Control System on CNG Fueled Vehicles using Machine Learning: A Case Study on the Downhill

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Abstract

Compressed Natural Gas (CNG) is an affordable fuel with a higher octane number. However, older CNG kits without electronic controls have the potential to supply more fuel when driving downhill due to the vacuum in the intake manifold. Therefore, this article presents a development of a CNG control system that accommodates road inclination angles to improve fuel efficiency. Machine learning is involved in this work to process engine speed, throttle valve position, and road slope angle. The control system is designed to ensure reduced fuel consumption when the vehicle is operating downhill. The results showed that the control system increases fuel consumption by 25.7% when driving downhill which an inclination of 5°. The AFR increased from 17.5 to 22 and the CNG flow rate decreased from 17.7 liters/min to 13.8 liters/min which is promising for applying to CNG vehicles.

Keywords: CNG; Control system; Road inclining angle; Fuel saving; AFR; Machine learning

1. Introduction

In the recent decade, there is an imbalance between the stock of fossil energy in the market and demand which is causing the continuity of the global energy crisis. This is indicated by an equitably high upward trend of global energy consumption from 2015 [1], [2] due to the increase in the population and number of vehicles [3]. It was also reported that the amount of fossil energy production at the global level (OPEC and non-OPEC) is highly inadequate in addition to the recent impact of war [4], [5], thereby, leading to a significant increase in the oil price which subsequently affects the transportation sector, especially the automotive industry. Therefore, grid technology and renewable energy are currently being developed to mitigate the dependence on fossil as indicated by the promotion of Electric Vehicles (EVs), Hybrid Vehicles (HVs), and Fuel Cells Vehicles (FCs) [6]. This EVs, HVs, and FCs technology is quite promising for reducing emissions, dependence on fossil energy, and energy consumption. However, this technology has certain drawbacks, such as limited mileage, inadequate infrastructure, and high ownership costs. This means there is a need to develop a fuel with low and environmentally friendly emissions, and more competitiveness towards renewable energy such as biofuel [7] and Compressed Natural Gas (CNG) [8].

CNG can be operated on high compression engines due to its high octane number making it suitable for both light duty vehicles and high duty vehicles [9], [10]. CNG has more potential to be developed as an environmentally friendly fuel in the future compared to LPG. Research on CNG for vehicles continues to develop, for example mixed with diesel [11], development of pressure reducing components [12], and application of CNG mixed with hydrogen [13]. However, scientific reports related to modification of the control system for fuel economy have not been widely discussed.

Other studies have discussed emissions from CNG-powered engines in comparison to other fuels [14]. In addition, observations regarding emissions and driving behavior in vehicles with bi-fuel technology (gasoline-CNG) have also been reported with hundreds of samples [15]. However, the two studies have not discussed in detail the level of fuel consumption. Several studies have also attempted to improve the capabilities of the CNG engine by controlling its operations using an injection system [16]–[18]. Xu [16] applied pilot injection to diesel engines and efforts were also made to use this method in the CNG fuel system. Yuvenda [17] later set the injection duration with the Pulse Weight Modulation (PWM) system while Nguyen [18] observed the application of CNG with single-point injection. These studies simply focus on the usage of CNG injection without considering fuel economy.

The stoichiometry AFR value of CNG has become a subject of research targeted toward achieving the most optimal emission released [19]–[21]. The study conducted by Kar [19] dan Wang [20] showed that the performance of the CNG engines can be determined through stoichiometry AFR values in the range of 17.5. Geok [21] also focused on the relationship between the AFR and the power indicator value produced by the CNG engine. These studies demonstrated the possibility of determining CNG engine performance through AFR stoichiometry but none focused on achieving lean AFR.

Previous studies have also used Computational Fluid Dynamics (CFD) software to simulate CNG engine performance [22], [23]. It was used by Sadah [22] to analyze the components of the air and CNG mixer mounted on the intake manifold at different flow characteristics while Alrazen [23] applied it to analyze the performance of CNG under operation in a diesel engine. The two studies focus on the mixture of air and CNG without any consideration for the performance of the associated engines when operating on lean mixtures. It is also important to note that the different torques produced by a CNG engine have also been studied through the changes in the dual sequential ignition system [24] but the impact of the ignition system on consumption was not examined.

Several studies have started developing Artificial Intelligent (AI) to manage CNG generally using some model-scale control systems before their implementation in real conditions [25], [26]. Lino and Maione [25] designed the CNG common rail engine technology focused on injector control and used dynamic modeling to describe its operation by mixing CNG with hydrogen gas to produce Hydrogen enriched Compressed Natural Gas (HCNG). Meanwhile, Huang and Ma [26] observed changes in HCNG when the engine was running and applied quadratic polynomial modeling to simulate the CNG variations. These studies focused on the design model for the CNG engine but failed to consider modeling the control system to increase fuel economy. Other studies have also used Artificial Neural Network (ANN) and Artificial Neuro-Fuzzy (ANFIS) control CNG-fueled engines [27], [28] such as its application in predicting the usage of CNG in diesel engines by Roy *et al.* [27]. There is, however, no focus on the usage of AI in the control system to economize CNG so this is a novelty in this research.

This means that various CNG system variables have been researched and developed but fuel economy modeling on selected road conditions has not been widely discussed. It is important to note that vehicles often operate on roads under different conditions. For example, countries with a lot of mountainous terrains have downhill roads and the movement of vehicles on these roads requires that speed is supported by the kinetic force (A) which is usually influenced by the vehicle mass and the earth's gravity (B) as indicated in **Figure 1**. This kinetic force, however, has the potential to be developed as a CNG control system to improve fuel saving. Therefore, this study designed a CNG control system using AI to increase fuel efficiency with due consideration for the downhill. The focus was to apply the model to a real engine and also to produce the mathematical modeling using the MATLAB Simulink software.

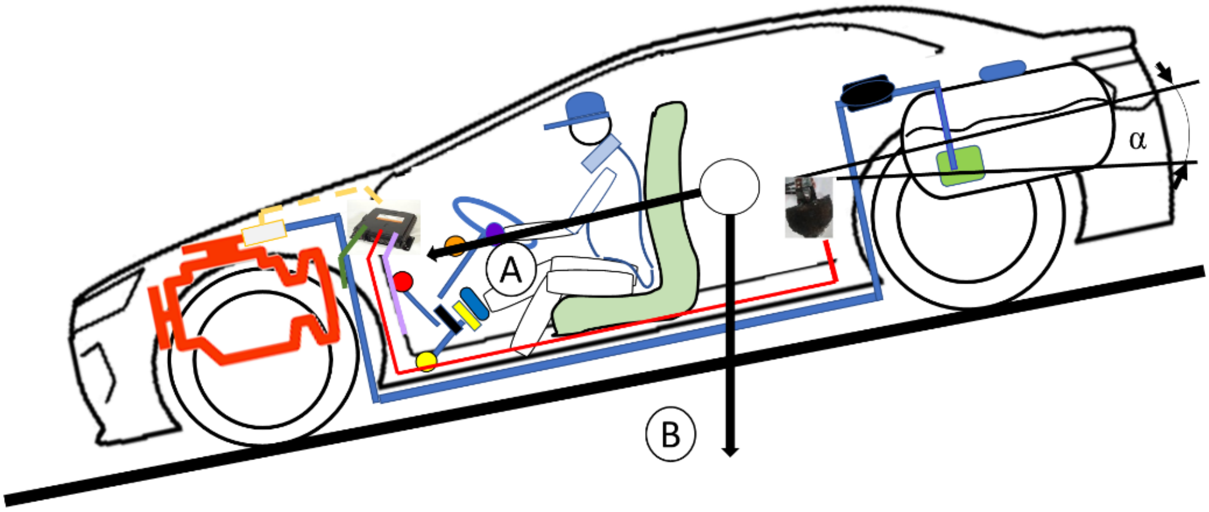

Figure 1. The kinetic force on the vehicle driving on the downhill

2. Methods

The consideration of several untapped variables and potential gaps observed in CNG system development led to the design of a CNG control system that focuses on the road inclining angle with the objective of increasing fuel efficiency. This was achieved using Artificial Intelligence (AI) or machine learning indicated in the prototype presented in **Figure 2**. The control system was designed to work based on input from the speed sensor (5) and throttle position sensor (4) while the road inclining angle (8) was used to control CNG flow through the injector or solenoid (9). Moreover, the fuel economy was controlled by the electronic control system or ECU (7), and the CNG used was stored in a tank (1) operating at pressures up to 200 bar. The pressure was later lowered by a reducer (2) while the vacuum was regulated using the vacuum controller (3). It is pertinent to note that the signal of the speed sensor (5) was initially processed through the speed controller module (6) before entering the ECU.

2.1. *Experimental Setup*

The data retrieval setup was used to support the test procedures implemented for the designed control system using the data obtained in real-time. The dynamics of the CNG flow rate in the fuel line were determined by the flow sensor (a) and validated using a flow meter (9) installed in series. Moreover, the position of the road inclining angle was measured by the road inclining angle sensor (b) and validated by the bevel gauge while the mixture of the air and CNG entering the engine was controlled by the throttle valve sensor (TPS) (4,c) producing an analog signal which was read by the microcontroller (g). The Air to Fuel Ratio (AFR) between air and CNG fuel was evaluated by the oxygen sensor (8, e) mounted on the muffler and the readings were validated by the AFR meter (11) and the Engine Gas Analyzer – EGA (12). Furthermore, the engine speed was determined by the speed sensor (5, d) installed on the crankshaft while the speed module (6, f) was applied for signal conditioning which was further evaluated by the data acquisition microcontroller (g), and the data were displayed on the computer (h) as shown in **Figure 3**.

The fuel tank (1) was used as a CNG reservoir with a pressure of approximately 200 bar which was first lowered by the reducer (2) to 2-4 bar before entering the engine. The vacuum controller (3) was used to modify the CNG to enter the engine according to the needs. It is important to note that the developed control system (7) was embedded with a fuzzy logic controller to control the CNG. The setup to collect data and test the model developed is presented in **Figure 3** and **Figure 4** while the equipment specifications are listed in **Table 1**.

The architecture of the CNG control system designed is presented in **Figure 5** and it was discovered to have three items which include sensor input, actuator output, and gas flow control system. The ECU used a Fuzzy Logic Controller (FLC) to regulate the flow of CNG and this was achieved by comparing the positions of three sensors with the application of the throttle position, engine speed, and road inclining data as input. Moreover, the analog signals from these sensors were converted into mathematical logic using the ADC. It is also pertinent to note that the FLC effectively controlled all three sensors to regulate the flow of CNG. This was achieved through a comprehensive approach with due consideration for the data from all three sensors based on mathematical logic.

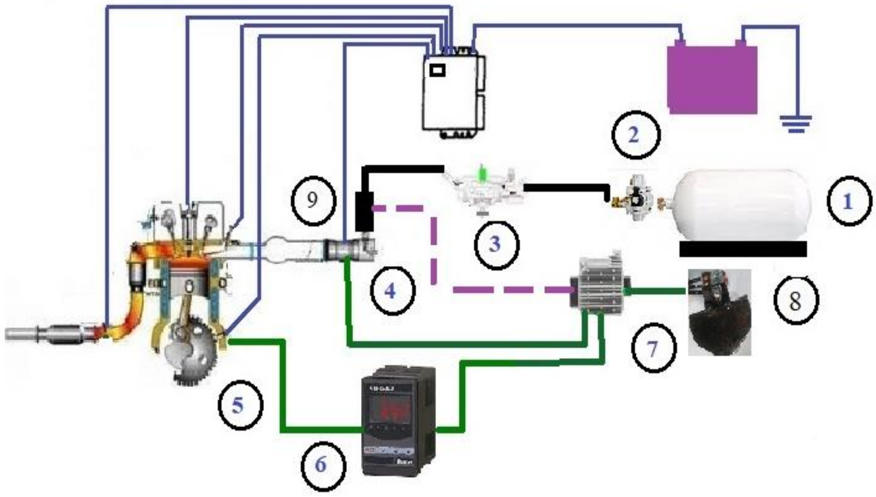

Figure 2. The concept of a CNG control system considered road inclining angle

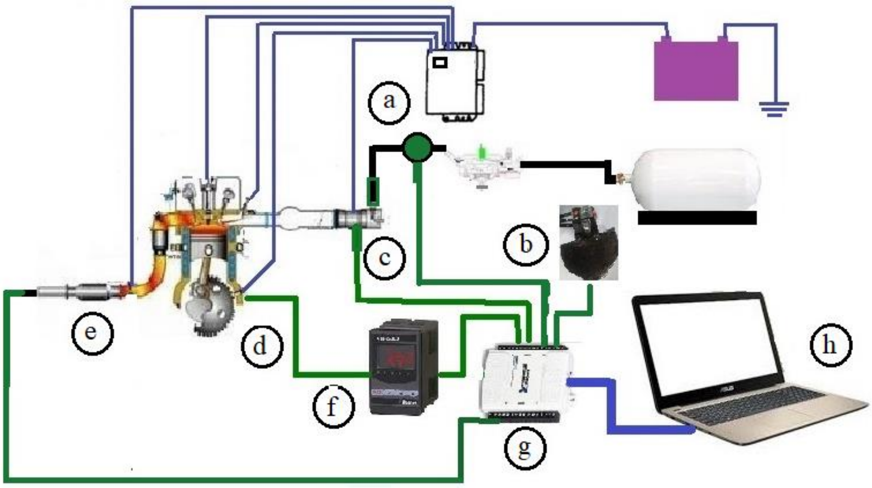

Figure 3. Data acquisition on the designed CNG control system

Figure 4. Data collection for the designed CNG control system

Table 1. Research equipment and specification

No	Description	Specification
1.	Data acquisition	Microcontroller NI type 6008
2.	Modul speed	Autonic (CN- 6100 and MP5Y – 44)
3.	Speed sensor	Digital type sensor
4.	TPS	Analog-type sensor
5.	Data acquisition computer	Laptop with RAM of 8 GB, operating system of 64-bit, and hard drive of 1 TB
6.	Engine	Volume 1500 cc, four-stroke engines
7.	Reducer	Spring regulator type
8.	Fuel tank	Operating pressure 200 bar
9.	Flow sensor	Measuring area 0 -100 liter/minute
10.	Flow meter	Digital type measuring range 0 – 100 liters/minute
11.	AFR meter	Digital type
12.	EGA	Four gas analyzer model SY-GA401
13.	Road inclining angle sensor	Analog sensor
14.	Control system	ATMEGA 32 microcontroller, transistor, and other electronic components

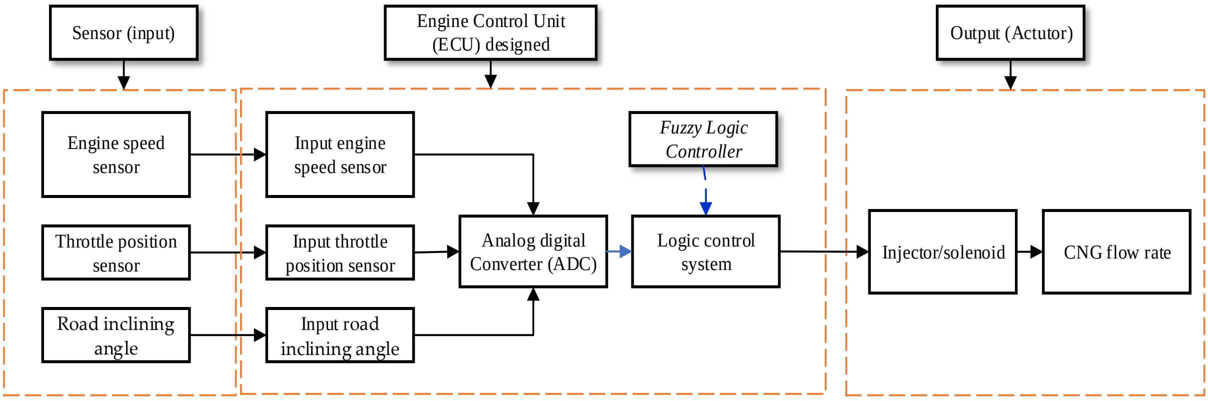

Figure 5. Logic block diagram to analyze the CNG control system

2.2. *Design of Control System Model*

The CNG control system with road inclining angle was developed using machine learning through several steps. The initial process involved designing the model using MATLAB Simulink containing several mathematical equations while further step focused on developing a CNG control system to be applied to a real engine. The model designed is presented in **Figure 6** and it has three main parts which include the input, engine model, and output. The input consists of three components which are the throttle position sensor, engine speed sensor, and road inclining angle sensor, the engine model has four subsystems such as the intake manifold dynamic, CNG dynamic, engine dynamic, and AFR dynamic while the output is the simulation result of the designed control system. It needs more attention to the intake manifold dynamics because it is used to model air movement into the engine from the flow and pressure side. In contrast, the CNG dynamics model the behavior of the flow of CNG entering the engine. A Fuzzy Logic Controller (FLC) was also applied to economize the CNG entering the engine according to the most appropriate conditions. Furthermore, the engine dynamics was used to model the changes in torque and engine speed according to the conditions desired by the driver while AFR dynamic describes the mixture of air with CNG at different engine conditions.

2.3. *CNG Dynamic*

The CNG dynamic model was designed to have three components which include the CNG volumetric efficiency, FLC, and CNG flow. The volumetric efficiency used is presented in **Figure 7** based on the reference to previous studies [29] and was determined using the properties of methane (CH_4) which is the largest constituent of CNG gas. Paying attention to the volumetric efficiency in this study is determined by the constituent elements, and the engine speed is necessary.

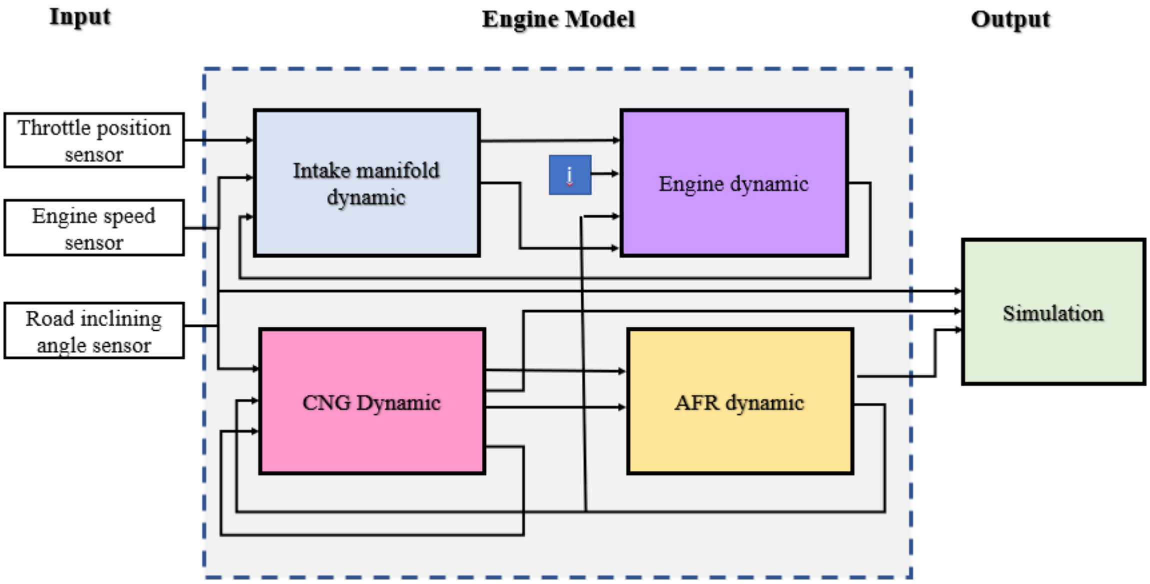

Figure 6. Designed CNG control system model with road inclining angle

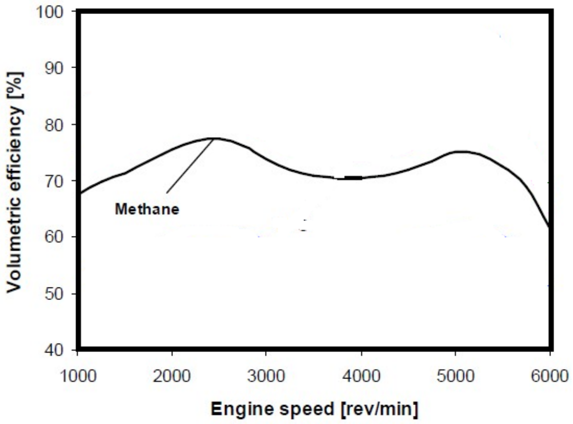

Figure 7. Determination of the CNG volumetric efficiency

FLC was used to improve the ability to save CNG fuel flow based on three inputs which include the throttle valve position, crank shaft, and road inclining angle sensors. The CNG entering the engine through the intake manifold was controlled by a vacuum controller and a solenoid/injector through the activities of the FLC. It is pertinent to state that the FLC was developed in reference to Table 2 while the air entering the engine through the intake manifold was calculated using Eq. (1).

$$\dot{m}_a = \frac{V_d \cdot N \cdot \eta_v \cdot \rho_a}{12 \cdot 10^7} \quad (1)$$

The mixture of air with CNG, known as AFR, was calculated based on the ratio of air ($\dot{m}_a$) to CNG entering the engine which is denoted as ($\dot{m}_f$) in (g/s) units. The CNG flow was calculated based on the ratio of the incoming airflow to the AFR CNG stoichiometry (AFR_{st}) as indicated in Eq. (2). The AFR CNG at the intake manifold before entering the engine was also calculated using on the intake airflow and CNG flow in Eq. (3).

$$\dot{m}_f = \frac{\dot{m}_a}{AFR_{st}} \quad (2)$$

$$AFR_{st} = \frac{\dot{m}_a}{\dot{m}_f} \quad (3)$$

2.4. *AFR Dynamic*

The AFR dynamic was used to model the process of mixing the airflow and CNG entering the engine using the design in Eq. (3). In real conditions, AFR CNG is usually measured by an AFR Meter validated by the Engine Gas Analyzer. Meanwhile, the AFR CNG modeling design on MATLAB Simulink is presented in Figure 8.

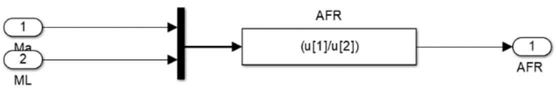

Figure 8. Modeling of AFR CNG

2.5. *Engine Dynamic*

The torque generated is normally used to lift the load based on the crankshaft rotation angle. Therefore it was calculated using the following Eq. (4) through the constant value, intake airflow, AFR of air and CNG, ignition timing, and engine speed [30], [31].

$$Torque_{eng} = -181.3 + 379.36.m_a + 21.91.AFR - 0.85.AFR^2 + 0.26.\sigma - 0.0028.\sigma^2 + 0.027.N - 0.000107.N^2 + 0.00048.N.\sigma + 2.55.\sigma.m_a - 0.05.\sigma^2.m_a \quad (4)$$

2.6. *Intake Manifold Dynamic*

The airflow in the intake manifold is strongly influenced by the position of the throttle valve angle. Therefore, the airflow after the throttle valve was calculated using Eq. (5) while the dynamics of the air pressure entering the engine were determined through Eqs. (6) to (10).

$$\dot{m}_{ai} = f(\theta) \cdot g(P_m) \quad (5)$$

$$f(\theta) = 2.821 - 0.05231.\theta + 0.10299.\theta^2 - 0.00036.\theta^3 \quad (6)$$

$$g(P_m) = 1;\ if\ \ P_m \leq \frac{P_{amb}}{2} \quad (7)$$

$$g(P_m) = \frac{2}{P_{amb}}\sqrt{P_m.P_{amb} - P^2{}_m};\ if \frac{P_{amb}}{2} \leq P_m \leq P_{amb} \quad (8)$$

$$g(P_m) = -\frac{2}{P_{amb}}\sqrt{P_m.P_{amb} - P^2{}_{amb}};\ if\ \ P_{amb} \leq P_m \leq P_{amb} \quad (9)$$

$$g(P_m) = -1;\ if\ P_m \geq P_{amb} \quad (10)$$

Engine speed causes several changes in intake manifold air pressure and air mass velocity depending on throttle valve angle, engine load, and environmental air pressure factors. In addition, the dynamics of air changes in the intake manifold and the velocity of the mass of air entering the engine are determined using the following Eqs. (11) and (12).

$$\dot{P}_m = \frac{R \cdot T}{V_m}(\dot{m}_{ai} - \dot{m}_{ao}) \quad (11)$$

$$\dot{m}_{ao} = -0.366 + 0.08979 \cdot N \cdot P_m - 0.0337 \cdot N \cdot {P_m}^2 + 0.0001 \cdot N^2 \cdot P_m \quad (12)$$

2.7. *CNG Control System*

The aim of the CNG control system designed was to determine the conditions needed to economize fuel usage. The machine learning method used was the FLC which works based on the MISO (Multiple Input Single Output) concept. The design of the FLC was tested at the early stages through simulation in MATLAB Simulink Software after which it was embedded in the ATMEGA 32 microcontroller. The microcontroller was combined with transistors and other electronic components to be subsequently assembled into an Engine Control Unit (ECU) which was subsequently applied to control the CNG under actual engine conditions. It is pertinent to reiterate that the inputs of the FLC include a road inclining angle sensor, an engine speed sensor, and a throttle valve sensor.

The engine speed sensor is a digital sensor installed on the crankshaft as indicated in **Figure 4** to determine the speed of the engine. The signal generated by this sensor is clustered on the FLC which is considered in determining the pattern of the CNG control system. The clusters are in 3 levels which include low with 0 – 1000 rev/min, medium with 800 – 4200 rev/min, and high with 3200 – 5000 rev/min and were used as a membership function for engine speed identification as presented in **Figure 9**.

The throttle valve sensor is an analog sensor operating in the 5-volt area and was used to determine the acceleration of the engine based on the position of the throttle valve opening angle. Its input operates with due consideration for the CNG control system and is also designed to be a membership function in FLC based on three clusters which include the low cluster with an opening angle between 0 – 22, medium between 10 – 80, and high in the range of 65 – 100 as indicated in **Figure 10**.

The road inclining angle sensor produces an analog signal with an operation range of 5 volts and works based on the attached gravity weight. The results produced by the sensor were used as a membership function in the FLC which is the main parameter in designing the CNG control system. The membership function of this sensor is also divided into three clusters which include a low cluster with an angle between 0 – 4, medium between 3 – 35, and high between 25 – 50 as presented in the following **Figure 11**.

The logic of the CNG control system designed to improve fuel economy is presented in Table 2 and its achievement is tagged as the eco mode which is believed to have been attained when the road inclining sensor, throttle valve, and road inclining angle sensor are in the medium and high range. Moreover, the CNG efficiency is focused on the period when the vehicle is on a downhill road and the speed is forced by gravity and vehicle mass, thereby, supporting the engine power to save CNG fuel.

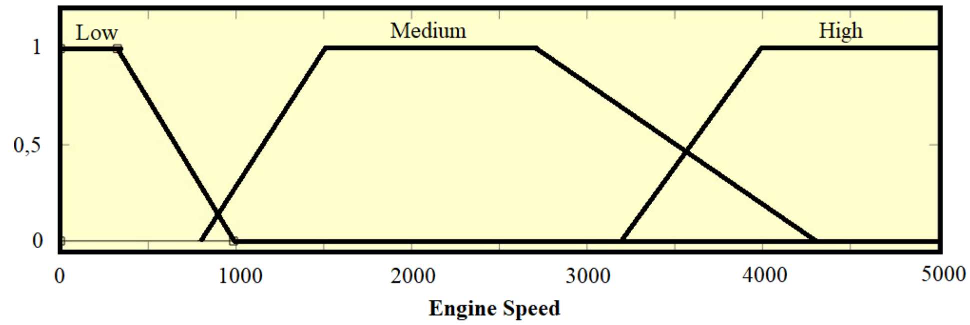

Figure 9. Membership function of engine speed

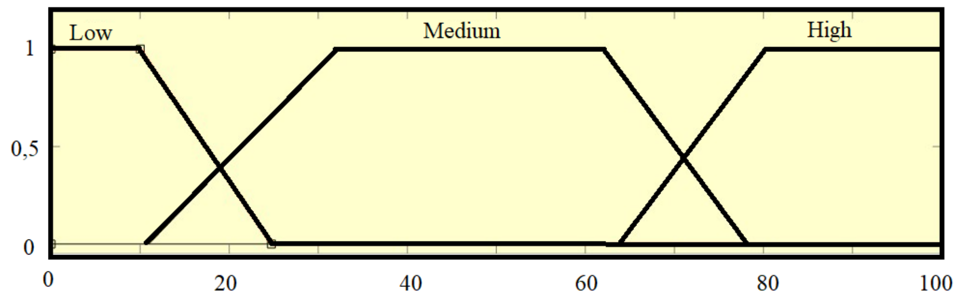

Figure 10. Membership function of throttle valve position

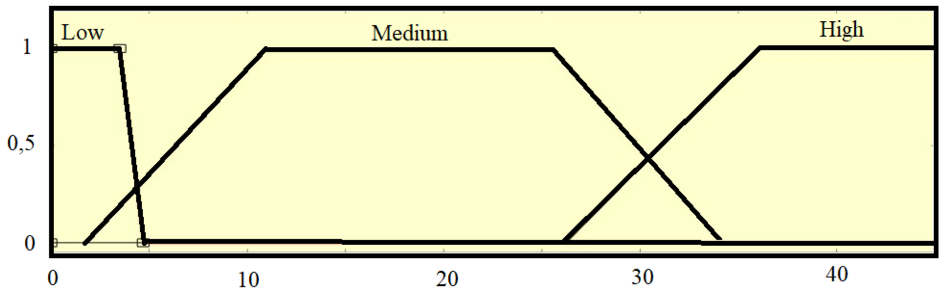

Figure 11. Membership function of road inclining angle

Table 2. Control system logic

No.	Engine speed (rev/min)	Throttle valve position sensor (degree)	Road inclining angle sensor (degree)	Economy mode
1.	1	1	1	Off
2.	1	2	1	Off
3.	1	1	2	Off
4.	1	1	3	Off
5.	1	3	1	Off
6.	1	3	2	Off
7.	1	2	3	Off
8.	1	1	3	Off
9.	1	2	3	Off
10.	2	1	1	Off
11.	2	1	2	Off
12.	2	2	2	On
13.	2	3	3	Off
14.	2	2	3	On
15.	2	3	2	On
16.	2	1	3	Off
17.	2	3	1	Off
18.	2	2	1	Off
19.	3	1	1	Off
20.	3	2	1	Off
21.	3	2	2	On
22.	3	2	3	On
23.	3	3	3	On
24.	3	1	3	Off
25.	3	3	2	On
26.	3	1	1	Off
27.	3	1	2	Off

Notes: Low = 1, Medium = 2, High = 3

3. Results and Discussion

The CNG Control System used machine learning to recognize the most appropriate conditions to improve CNG efficiency. Moreover, the fuzzy logic controller (FLC was used as the artificial intelligence (AI) or machine learning to make decisions related to increasing CNG efficiency using the rule presented in Figure 12. The figure explains the membership function of the three sensors used as input and the decisions taken to drive the actuator.

Figure 12 explains the movement position of the actuator based on sensor input while the three-dimensional graph in Figure 13 indicates the decision-making process and the continuation of the FLC rule. Moreover, the sensors and actuators were observed to have a clear correlation in control system. Figure 14 to Figure 16 show the results of signal measured on the sensor.

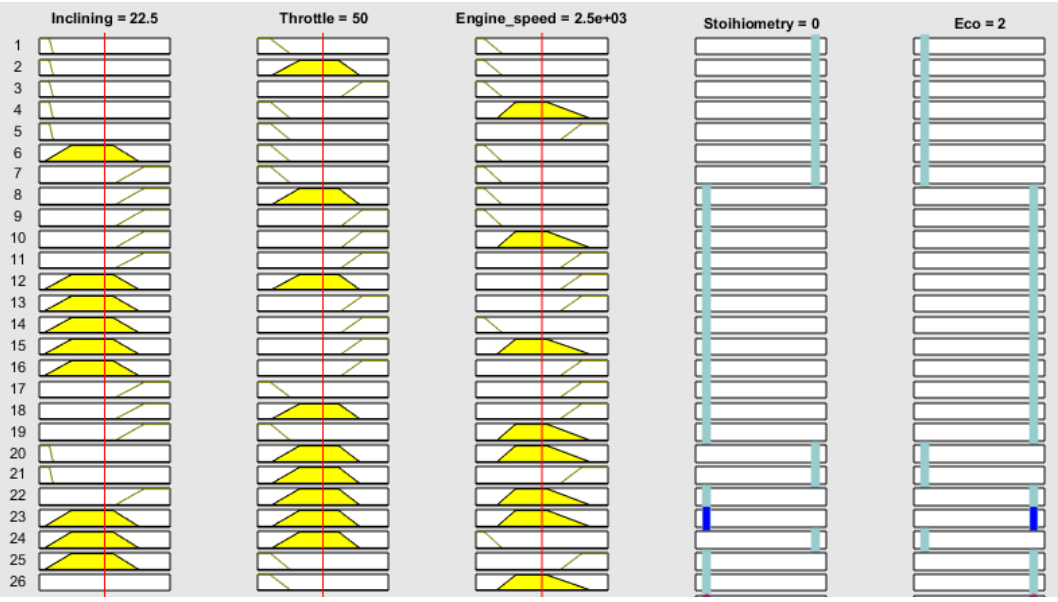

Figure 12. Fuzzy logic controller (FLC) rule

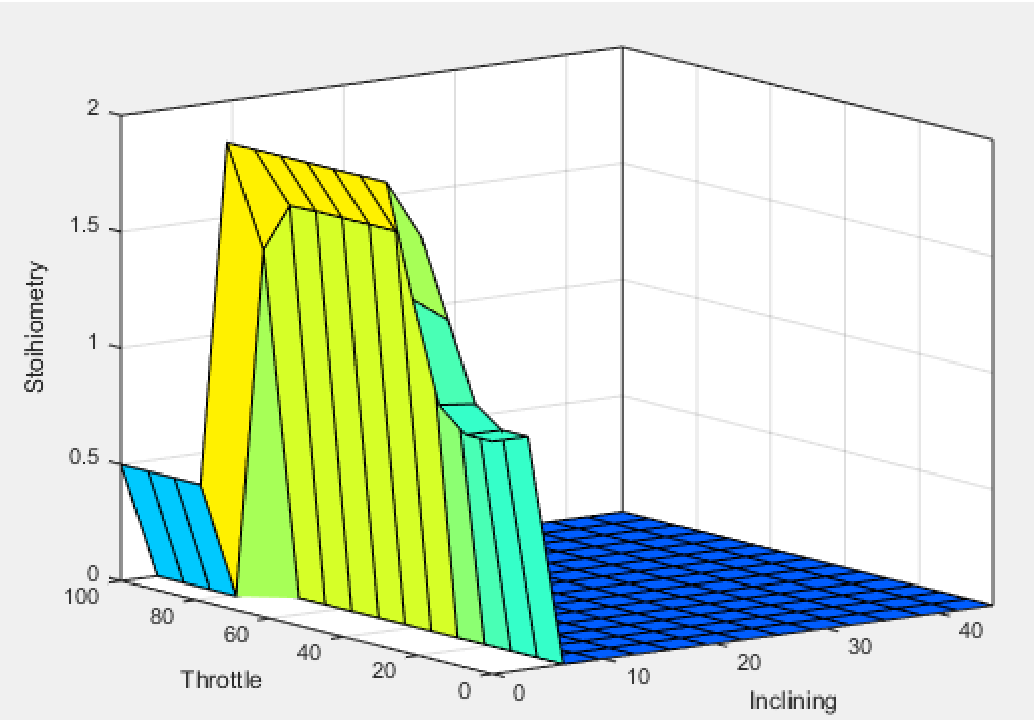

Figure 13. Relationship decision-making on FLC

3.1. Throttle Valve Position Sensor Signal Measurement

The throttle valve position sensor signal was measured through the data acquired for several periods and validated using a bevel gauge and the data were converted into information on the position of the throttle valve opening angle. It is important to note that the signal sensor was designed to have three functions which include operating as an input for the CNG control system, simulation data on MATLAB Simulink, and data acquisition. Moreover, an analog throttle valve position sensor signal including a linear signal was used in the system and observed to have operated for 20 seconds as presented in **Figure 14**. The throttle valve position sensor was in the closed position (0°) in the first period from 0 to 4 seconds, opened at 5° in the second period from 5 to15 seconds, and closed again in the third period from 16 to 20 seconds.

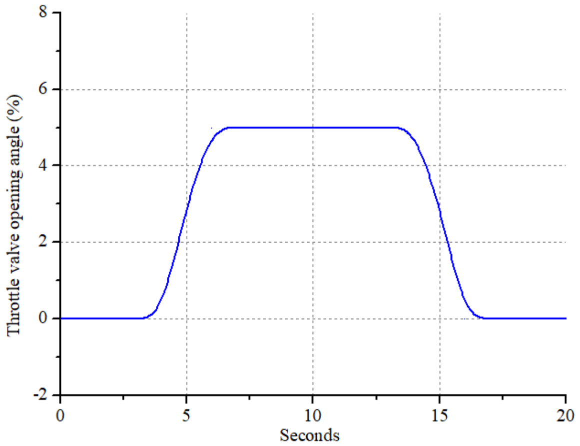

Figure 14. Results of the throttle valve position sensor

3.2. Road Inclining Angle Sensor Signal Measurement

This sensor signal was measured by acquiring data through the same method applied for the throttle valve position sensor. The process involved the validation of the sensor signal using a bevel gauge and converting the data to information related to the position of the road inclining angle. Moreover, it was also designed to serve three functions which include being an input in the CNG control system, simulation data on MATLAB Simulink, and data acquisition. It was discovered from the analog signal measured for 20 seconds in **Figure 15** that the sensor was in the 0° position which models the vehicle operating on a flat road in the first period from 0 to 4 seconds, moved to an angle of 5° to model the vehicle operating on a downhill road depressed at 5° in the second period from 5 to 15 seconds, and back to 0° position in the third period from 16 to 20 seconds.

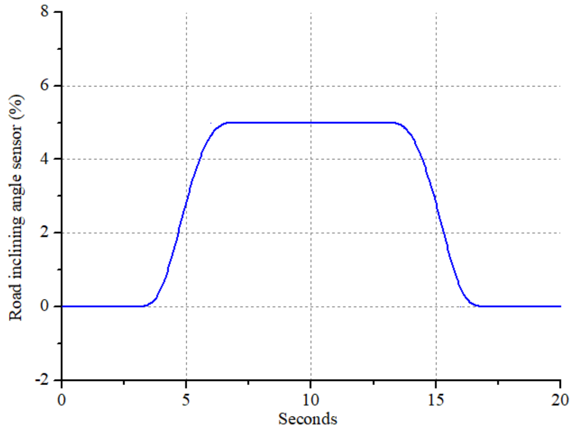

Figure 15. Results of the road inclining angle sensor

3.3. Engine Speed Measurement

The real engine speed was measured using an engine speed sensor validated using a digital tachometer after which the results obtained during the simulation for the CNG control system with road inclining angle and without the control system were compared. The measurement was also conducted for 20 seconds like the throttle valve measurement method and the simulation of the model without the CNG control system designed using a road inclining angle showed that the engine speed was in a stationary condition of ±800 rpm in the first period from 0 to 4 seconds when the throttle valve closed, opened to 5° and the engine speed increased from ±800 rpm to ±1000 rpm in the second period from 5 to 15 seconds, and closed again with the engine speed rotating back to a stationary condition in the third period from 16 to 20 seconds.

The CNG control system designed using road inclining angle model was simulated and the results showed that the engine speed was in a stationary condition of ±800 rpm in the first period from 0 to 4 seconds when the throttle valve closed. The value increased from ±800 rpm to ±950 rpm in the second period from 5 to 15 seconds when the valve was opened to 5°, and the engine speed rotated back to a stationary condition in the third period from 16 to 20 seconds when the valve closed again.

The engine speed simulated on MATLAB Simulink for the model designed also showed that the engine speed was in a stationary condition of

±800 rpm in the first period from 0 to 4 seconds when the throttle valve closed. The value increased from ±800 rpm to ±1000 rpm in the second period from 5 to 15 seconds when the valve was opened to 5°, and the engine speed rotated back to a stationary condition in the third period from 16 to 20 seconds when the valve closed again. It was also discovered from the measurement made using the real condition that the throttle valve position has almost the same rotation in the range of ±800 rpm for all the models tested but there is a difference when the throttle valve was opened 5° for the CNG control system with the road inclining angle. This simply shows that the application of this model was able to reduce the CNG flow entering the engine and consequently the engine speed but this is not expected to be a problem when applied to the actual vehicle due to the fact that it is moving downward. It is also pertinent to note that the speed of the vehicle was also assisted by its mass and the gravitational force of the earth. The comparison of the engine speed between real and simulated conditions is presented in the following Figure 16.

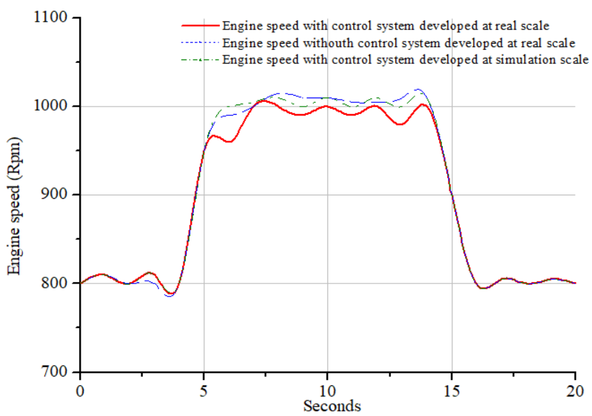

Figure 16. Result of engine speed similation

3.4. *CNG Dynamics*

The test for the CNG dynamics includes measuring the AFR and CNG flow as indicated in Figure 17. The process involved installing an oxygen sensor in the exhaust gas line as presented in Figure 4 and the signal produced was validated using an AFR meter and an Engine Gas Analyzer. The test was also divided into several periods with a focus on the three models which include the model with a CNG control system designed using a road inclining angle, without the CNG control system, and simulation through MATLAB Simulink. It was discovered that the AFR for all the models was in the range of 17.5 (stoichiometry area) in the first period from 0 to 4 seconds with a closed throttle valve and the engine speed at ± 800 rpm. Meanwhile, in the second period from 5 to15 seconds when the throttle valve was raised at an open angle of 5o and the engine speed was at ± 1000 rpm, the AFR in the model without the CNG control system was found to be 17.5 (stoichiometry area) but the value increased to 22 when the CNG control system designed with road inclining angle was used. The increment indicates a reduction in the flow of CNG into the engine and that the air mixture was getting more or less, thereby, saving the usage of fuel. The findings also showed that the AFR increased in the range of ± 22 using MATLAB Simulink simulation and this is up to 25.7% from the stoichiometry position. It is important to note that there is a slight difference in the AFR value between the simulated and real conditions of the CNG control system designed using the road inclining angle. This is indicated by the constant increase in the value during the simulation conditions and the slight increase associated with some delays in the real conditions. The delay is believed to be due to the processing time for the AFR reading on the measuring instrument.

It was discovered that ±22 is the fuel-saving region for the AFR and this is the target of this study. Therefore, it can be stated that this result is beneficial in terms of achieving savings compared to the previous studies such as [32] which focused on controlling AFR in the stoichiometry range to reduce disturbances, [33] application of a wood chipper engine working in the stoichiometry range, and [20] effort to develop a mixer for air and CNG in the area of stoichiometry. This means these studies only focused on the AFR stoichiometry without saving fuel.

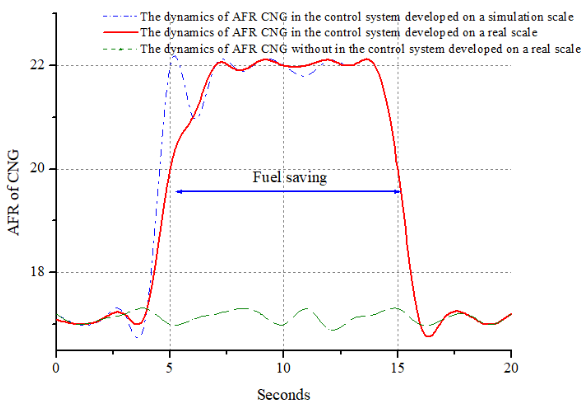

Figure 17. AFR dynamics

The model designed was observed to have saved fuel both in the AFR dynamics and the CNG flowing into the engine. This is indicated by the CNG flow measured using the sensor in Figure 3 and validated through a flow meter in liters/minute. It is important to note that the process was also conducted for the model designed, without the model, and through simulation using MATLAB Simulink. The findings showed that the CNG flow was in the range of 12.2 liters/minute for all in the first period from 0 to 4 seconds with a closed throttle valve and engine speed set at ±800 rpm. Meanwhile, when the throttle valve was raised at an open angle of 5 and the engine speed was ±1000 rpm in the second period from 5 to 15 seconds, the flow of CNG in the model without a CNG control system reached 17.7 liters/minute but approximately 13.8 liters/minute for the CNG control system with a road inclining angle. This means there is a significant difference of 5.5 liters/minute between the two systems. This difference shows that the model developed was able to reduce the flow by up to 28.3% and the trend was observed to be almost similar in the simulated and real conditions except for a slight delay in the real scale. The delay is perceived to have been caused by the reading process on the CNG flow measurement. Moreover, the specific CNG flow dynamics are presented in Figure 18.

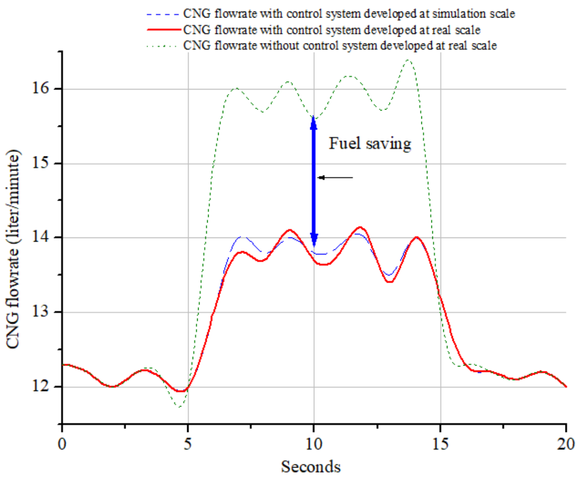

Figure 18. CNG consumption

4. Conclusion

The findings showed that the CNG control system with road inclining angle designed using machine learning has the ability to improve fuel economy. This was observed when the throttle valve was opened at the medium position of more than 4°, the road inclining angle was at a medium range of more than 4°, and the engine speed was also in the medium range of more than 900 rpm. The road inclining test conducted at 5° represents when the vehicles operate on a downhill road and the results showed that the fuel was economized as indicated by the 25.7% increase in CNG AFR from 17.5 to 22 and a 28.3% decrease in CNG flow from 17.7 liters/minute to 13.8 liters/minute. Moreover, the engine speed reduced slightly when the throttle valve was increased by 5° using the model designed due to the decrease in the CNG flow entering the engine.

This means the machine learning applied used an FLC to identify the most appropriate conditions to save the usage of CNG fuel. The model designed can provide a clear picture of the working control system because the accuracy was determined by comparing the simulation results with the real engine conditions and the difference was found not to be significant at less than 5%. It is important to note that the model has not been tested.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Competing interests

The authors declare no competing interest.

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Nomenclature

$\dot{m}_a$	Airflow in the intake manifold (g/s)
V_d	Volume engine (m³)
N	Engine speed (Rpm)
η_v	Volumetric engine efficiency refers to methane in percent (%)
ρ_a	Air density 1.2 kg/m³
$\dot{m}_f$	CNG flow (g/s)
AFR_{st}	AFR stoichiometry CNG
$Torque_{eng}$	Engine torque (N.m)
σ	When ignition on the engine
$\dot{m}_{ai}$	Dynamics of air flowing after throttle valve (g/s)
θ	Throttle valve opening angle (degree).
P_m	Pressure on the intake manifold (bar)
P_{amb}	Ambient air pressure (atmosphere – bar)
$\dot{P}_m$	The dynamics of air pressure changes (bar/s)
T	Air temperature (Kelvin)
R	Specific constant gas
V_m	Volume in the intake manifold space (m³)
$\dot{m}_{ao}$	Air mass velocity in the intake manifold (g/s)

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