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Modelling Fuel Cut Off Controller on CNG Engines Using Fuzzy Logic: A Prototype

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***Abstract*— Compressed Natural Gas (CNG) is an alternative solution to the limited availability of fossil energy. CNG use's advantages include high octane value, applicable to vehicles requiring large power, cost-effectiveness, and lower emissions. However, applying the old CNG kit leaves emission problems and fuel wastage during deceleration. Although numerous studies have been carried out with numerous variables to improve engine performance and emissions, reports regarding deceleration interventions are still limited. Therefore, this study proposes enhanced modeling to optimize the fuel cut-off controller by applying fuzzy logic by controlling the throttle valve position based on the input sensor of the engine. Engine dynamics, fuel characteristics, and intake systems are considered strictly in the development of the control system to obtain more precise results that refer to the complete combustion process. The designed model has advantages over previous studies, which focused on achieving CNG AFR stoichiometry to improve fuel economy by using the fuel cut-off method during deceleration. The results showed that fuel savings could be increased during deceleration by cutting off fuel flow to the engine. This can be seen from the increase in AFR ± 57% and decrease ± 38% - 67% in CNG flow rate during deceleration which is promising to be widely applied. In the future, the proposed model could be used as part of the vehicle component in optimizing the fuel consumption that will support green technology sustainability.**

***Keywords*— CNG; fuel cut off; controller; fuzzy logic.**

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I. INTRODUCTION

In the last decade, the increase in energy consumption has become an important concern in the development of automotive technology. According to EIA [1], global energy consumption growth has continuously increased since 2015 and is predicted to rise at an exponential trend until 2040. Furthermore, the population of motorized vehicles continues to increase with a drastic decrease in fossil energy production at the global level (non-OPEC and OPEC) [2], [3]. Therefore, this led to the development of flexi fuel vehicles [4], electric-based propulsion systems [5] and fuel cells vehicles [6] as an effort to mitigate the issue of oil availability. Electric vehicles and fuel cell s are logical choices regarding emissions and energy consumption [7]. However, there are some inconsistencies associated with both alternatives. EVs require a long-time to charge, with limited infrastructure availability and a high cost of ownership. Meanwhile, FCs are not yet commercially available with uncompetitive hydrogen prices [8]. Therefore, cleaner and more competitive alternative fuels, such as Compressed Natural Gas (CNG) and biofuel, are needed for 100% electricity-based propulsion and renewable energy transition [9].

CNG is an alternative fuel with numerous advantages, including having a high-octane value, being applied to vehicles requiring large power, having cheaper prices, and producing lower emissions [10]. Studies on CNG continue to be pursued to improve its capabilities continuously. For instance, Hosmath [11] carried out an experimental study to reduce emissions in diesel engines using mixed methods, while Aslam [12] developed CNG reducer control, and Lather [13] mixed it with hydrogen. However, none of these studies explicitly focused on improving CNG savings, and this paper has successfully developed a model that could improve CNG savings. Furthermore, studies on emissions other than toxic gas content continue to be conducted [14]. These studies were associated with observing the Particle Number (PN) produced by CNG-fueled vehicles compared to those with other alternatives, such as methanol, LPG, etc. According to Gha, Reza, and Ahmadikia [15], emissions from CNG-fueled vehicles are related to driving style. Experiments on 60 gasoline-CNG bi-fuel vehicles were observed comprehensively. Although both studies focus on the resulting emissions, none have considered how fuel efficiency is controlled.

Therefore, to improve the performance of CNG engines, enhanced injection methods were developed [16]–[18]. Xu [16] applied the pre-injection method on CNG vehicles compared to diesel engines. Yuvenda [18] reduced the time for its injection into the engine, while Nguyen [17] developed a model with one hole. These three studies focused on developing the injection method for engine performance without discussing the control system during deceleration. Furthermore, Geok [19], Muhssen [20], and Kar [21] carried out experimental studies on ways to achieve AFR stoichiometry values for CNG. Kar and Muhssen conducted the AFR stoichiometry approach to optimize the work of CNG engines. Geok observed the power indicator generated by the CNG engine based on calculating the AFR value. Although these studies led to a bright spot for optimizing the performance of CNG engines, they have not intervened to save fuel during deceleration.

Alrazen [22] and Sadah [20] used Computational Fluid Dynamics (CFD) software to predict the ability of CNG-fueled engines in their studies. Sadah [20] simulated a mixer on the design of a CNG reducer with CFD to determine the performance of the CNG flow during the mixing process. Alrazen [22] used CFD to model CNG characteristics mixed in a diesel engine. However, none of these studies discussed the process needed to improve the CNG simulation savings. Alper & Do [23] studied the torque variable generated by the CNG engine under various conditions and through the application of dual sequential ignition. This study only made improvements to the torque generated by changes in the ignition system variables without improving the consumption rate of the CNG engine.

In the last decade, studies on implementing control systems and artificial intelligence (AI) for machine management have been widely conducted with increased accuracy [24]. This is in addition to the development of control models to enhance CNG-fueled engines' controllability [25], [26]. Lino developed a dynamic modeling process to control the injector pressure on the common rail. Meanwhile, Huang and Ma designed quadratic polynomial modeling on a Hydrogen enriched Compressed Natural Gas (HCNG) engine. These methods aim to predict the use of diesel engines with added hydrogen gas.

Similarly, these two studies failed to design a control system model to increase CNG savings. Roy [27] introduced the application of Artificial Neuro-Fuzzy (ANFIS) and Artificial Neural Network (ANN) to predict the performance of CNG-fueled engines. These models were used to predict engine performance by adding CNG to diesel engines. However, this study has not been carried out to determine the engine control system settings despite the great potential of Artificial Intelligent (AI) technology in increasing CNG performance.

Numerous studies have been carried out on CNG with various variables. However, several have escaped the attention of researchers, including none yet to control CNG efficiency, apply artificial intelligence technology to CNG engine control systems, and increase CNG savings during deceleration. Therefore, this study proposes a new method to increase CNG efficiency or CNG savings during deceleration. The method is applied by developing a fuel cut-off controller when the engine operates in decelerating conditions to improve fuel economy by using fuzzy logic (AI). Hence, this study has developed a fuel cut-off controller model, as depicted in Fig. 1 to improve CNG saving while deceleration by using fuzzy logic. The designed CNG engine is a bi-fuel that operates with gasoline and CNG. Its engine parts consist of fuel tank (1), CNG reducer (2), crankshaft (3), throttle position sensors (4), solenoid/injector (5), and Engine Control Unit (ECU). Inputs from the crankshaft and throttle position sensors are used as fuel cut-off controllers in the ECU. It works when the engine speed is high and the throttle valve is closed (deceleration position). This model was demonstrated using the MATLAB Simulink software.

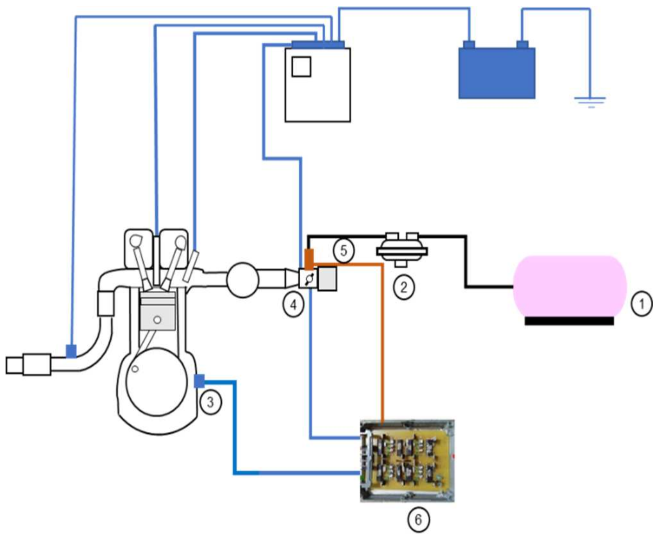

Fig. 1 The concept of the fuel cut off controller system modeled in this study: (1) fuel tank, (2) CNG reducer, (3) crankshaft position sensor, (4) throttle position sensor, (5) solenoid/injector, and (6) Engine Control Unit (ECU)

II. Material and Method

This research aims to improve the fuel economy of CNG engines. The method adopted by increasing the AFR value above the stoichiometry (17.2) at deceleration is presented in Fig. 2. This method is considered more promising than the previous researchers, which focused on achieving the AFR stoichiometry value [20], [28], [29]. Yang [28] studied AFR CNG stoichiometric with a stochastic basis to solve the uncertain cycle fluctuations of air masses and the mass of fuel entering the engine. Muhssen [20] designed a mixer to easily achieve the air and CNG mixing process in the AFR stoichiometric range. Wargula [29] observed the impact of a CNG-fueled chipper engine on AFR stoichiometry. The method in this study uses several stages, including input, modeling design, and output. Input as initial information and data for making modeling designs. Modeling design as the design of CNG engine model development. Finally, the output is the simulation result of the designed fuel cut off the controller.

A. Data Collection

The CNG engine model is made in several stages. The initial process takes engine speed data using the crankshaft sensor and opens the throttle valve sensor (4) on a real engine. The signal generated by the crankshaft sensor is digital. Furthermore, the signal from the crankshaft sensor (3) is conditioned to be made into a controller system (5). The analog signal resulting from signal conditioning is sent to the data acquisition system, with a microcontroller used to retrieve data (6). In the next process, the captured signal is stored in a computer (7). The data taken from the data acquisition is used to model the fuel cut-off controller.

CNG fuel is stored in a tank (1) with a gas phase at a pressure of ± 200 bar. The CNG reducer (2) lowers the pressure before it enters the intake manifold. The concept and set-up of data collection for engine speed and throttle valve position are shown in Figs. 3 and 4, respectively. The specifications of the equipment used in the study are also shown in Table 1. The modeling is carried out using the MATLAB Simulink software.

TABLE I
TOOLS AND DEVICES FOR DATA COLLECTION

No	Description	Specification
1.	Data acquisition	Microcontroller National Instrument (NI) 6008 32 channel.
2.	Signal Conditioning	MP5Y – 44 pulse meter, CN-6100-V1 (Autonomic)
3.	Crankshaft sensor	Digital fiber optic sensors.
4.	Throttle position sensor	Analog 0 – 5 volts.
5.	Computer CNG mathematical model design and data acquisition	Laptop with 64-bit operating system, 4GB RAM and 1TB hard drive.
6.	Engine	Gasoline engine injection system type, 4 cylinders
7.	CNG reducer	Vacuum type
8.	Fuel tank	Composite fibre reinforced metal

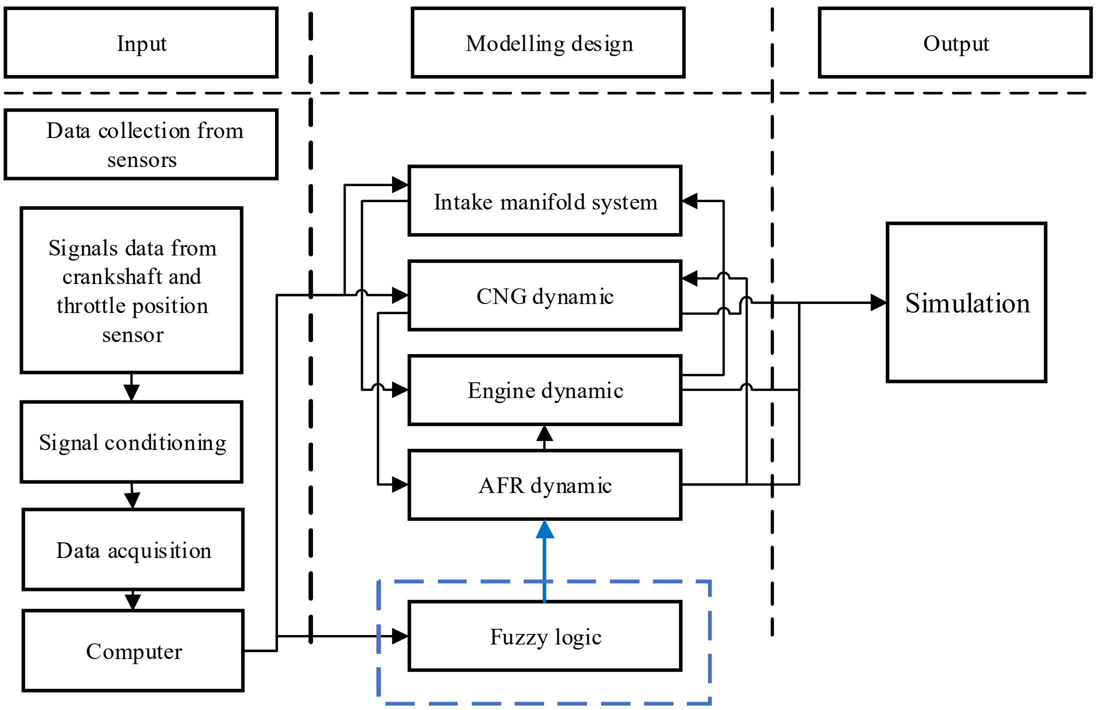

Fig. 2 The method used in the study

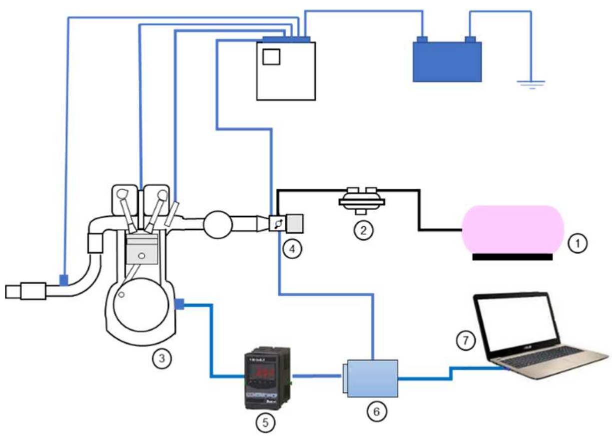

Fig. 3 Apparatus for data collection

Fig. 4 Set up the engine speed data collection process and throttle valve position

B. Modeling of Fuel Cut Off Controller

The CNG fuel system on an actual engine can operate appropriately with several support systems, including the engine and fuel systems. CNG mixture with air will enter the engine through the intake manifold. The designed CNG fuel system model must represent actual engine conditions. Therefore, the fuel system model designed includes engine dynamics, intake manifold system, CNG dynamics, and AFR system.

1) CNG dynamic: CNG Dynamic is a modeling of the CNG flow that enters the machine. In addition, AFR CNG with air is simulated in this model. The CNG flow that enters the engine is modeled based on Eq. (1). This flow consists of 5 variables, including the engine volume which is denoted by V_d in m3 units. Engine speed is denoted by N in units (rev/minute). η_v is the volumetric efficiency of CNG taken from methane in %. The density of air entering the engine is assumed to be 1.2 kg/m^3 with the notation ρ_a. The flow of air entering the engine in units (g/s) is denoted with m_a.

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

In this study, CNG is represented by methane (CH4) according to the Irimescu study [30]. The volumetric efficiency of methane used in the calculations is shown in Table 2.

The CNG flow entering the engine is denoted by m_f in units (g/s). It is obtained by comparing the airflow entering the engine with AFR CNG stoichiometry (AFR_{st}) in accordance with Eq. (2). AFR CNG from the engine is taken based on the ratio between the airflow entering the engine and the CNG flow, as shown in Eq. (3).

$$m_{f} = \frac{m_a}{AFR_{st}} \quad (2)$$

$$AFR = \frac{m_a}{m_f} \quad (3)$$

2) Engine dynamic: Engine dynamics are strongly influenced by the ignition that occurs in the combustion chamber. The torque generated by the engine is denoted as $Torque_{eng}$ in Nm. It is produced in the engine by several constraints, including airflow, AFR, ignition timing (σ), and engine speed (N), as shown in Eq. (4). The engine speed data used in this study was obtained through data acquisition on a real engine.

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

3) Intake manifold system: The air pressure dynamics in the intake manifold are shown in Eq. (5). $\dot{m}_{ai}$ is the airflow after the throttle valve in units (g/s) with the position denoted with θ in degrees. P_m is the intake manifold air pressure in units (bars) when the throttle valve is turned while operating the engine.

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

Changes in pressure in the intake manifold are strongly influenced by several constraints, including the ambient atmospheric pressure (P_{amb}) in bar units and the throttle valve position in accordance with Eqs.(6) to (10).

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

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

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

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

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

TABLE II

VOLUMETRIC EFFICIENCY OF METHANE

No.	Speed (rpm)	Volumetric efficiency (%)	No.	Speed (rpm)	Volumetric efficiency (%)
1.	800	0.660	15.	3600	0.710
2.	1000	0.680	16.	3800	0.705
3.	1200	0.690	17.	4000	0.705
4.	1400	0.710	18.	4200	0.705
5.	1600	0.725	19.	4400	0.710
6.	1800	0.745	20.	4600	0.720
7.	2000	0.760	21.	4800	0.745
8.	2200	0.770	22.	5000	0.755
9.	2400	0.780	23.	5200	0.760
10.	2600	0.780	24.	5400	0.745
11.	2800	0.755	25.	5600	0.720
12.	3000	0.745	26.	5800	0.670
13.	3200	0.730	27.	6000	0.630
14.	3400	0.720			

The engine used in this study does not use Engine Gas Recirculation (EGR). This is because it often undergoes several changes during operation, such as intake manifold pressure ($\dot{P}_m$) in bar/s units. This change can be calculated by the air temperature (T) d in kelvins, the specific gas constant (R), intake manifold volume (V_m) in m3, and the mass airflow rate ($\dot{m}_{ao}$) in g/s, as shown in Eqs (11) and (12).

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

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

Equations for engine dynamics and intake manifold dynamics were carried out under previous modeling publications [31].

4) Fuel *cut-off controller:* As a method to improve fuel economy, the fuel cut-off controller works by cutting off fuel when the engine speed is high while the throttle valve angle is low. To improve and optimize the CNG Engine performance, this model uses fuzzy logic, which has two inputs, as shown in Fig.7.

Engine speed as the input fuel cut-off controller has a membership function divided into three clusters, low, medium, and high, as shown in Fig. 5. The low cluster has a value of 0 – 2700 rev/min, medium 2200 – 4700 rev/min, and high 3200 – 5000 rev/min.

The throttle valve position becomes the second input of the fuel cut-off controller. Its membership function design is divided into 3 clusters: low, medium, and high, with 0 – 18°, 10 – 55°, and 48 – 100° opening angles. The membership function display for the throttle valve position is shown in Fig. 6.

The fuel cut-off controller logic decisions work based on engine speed conditions and throttle valve position. High speed and low throttle valve position indicate that the engine does not require large power. This is illustrated by the driver's reluctance to increase engine power by looking at the position of the throttle valve while running at high rpm, thereby increasing fuel economy (± 34% - 60%). The fuel cut-off controller logic is shown in Table 3, wherein the activation of the fuel cut-off indicates no fuel flow to the engine.

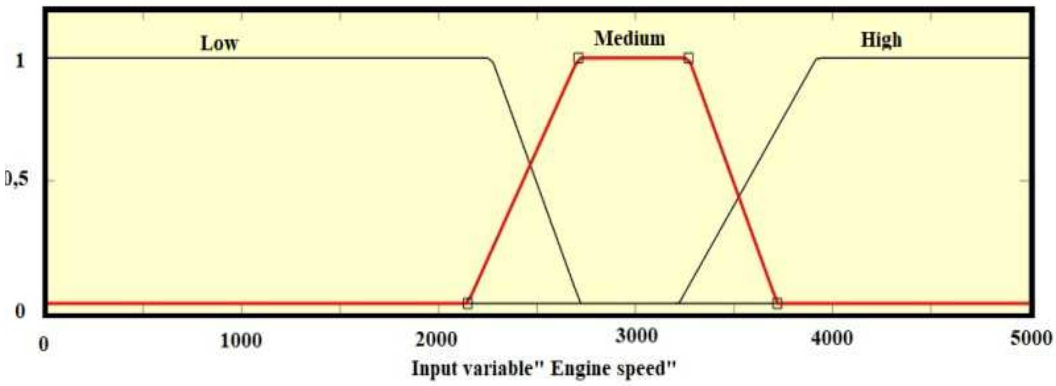

Fig. 5 Membership function engine speed

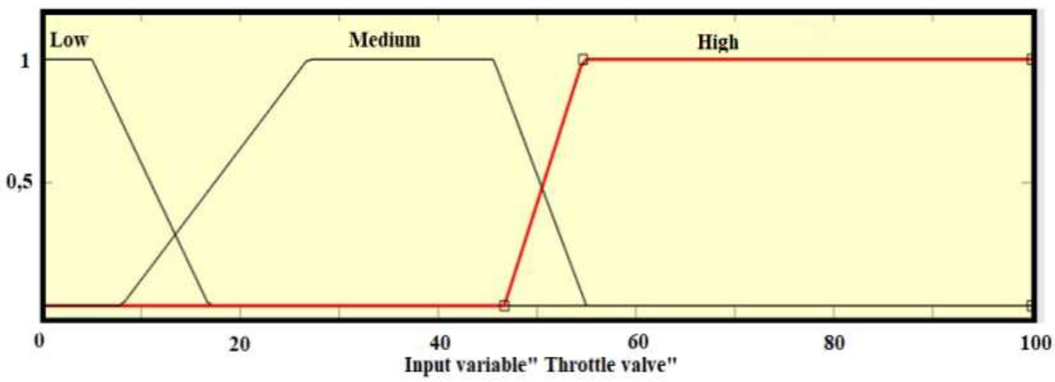

Fig. 6 Membership function throttle valve position

TABLE III
LOGIC OF FUEL CUT-OFF CONTROLLER

No.	Engine speed (rev/min)	Throttle valve position (degree)	Fuel cut off
1.	Low	Low	Off
2.	Low	Medium	Off
3.	Low	High	Off
4.	Medium	Low	Off
5.	Medium	Medium	Off
6.	Medium	High	Off
7.	High	Low	On
8.	High	Medium	Off
9.	High	High	Off

III. Result and Discussion

A. *Model Fuel Cut Off Controller on CNG Fuelled Engines*

The fuel cut-off model design on a CNG engine is shown in Fig. 7. The modeling adopted by increasing the AFR value above the stoichiometry of 17.2 at deceleration. This method is an advantage over the research methods carried out in the previous period, which focused on achieving the AFR stoichiometry value. This model has 4 sub-systems that work based on fuzzy logic, including CNG and AFR dynamics as well as intake manifold and engine systems. CNG dynamics and fuzzy logic work by modeling CNG's flow into the engine, thereby improving fuel economy. AFR dynamics display the air and fuel mixture according to stoichiometry conditions when there is an increase in CNG savings. The intake manifold system models the flow of air entering the engine and the dynamics of the throttle valve position. Meanwhile, the engine system models the torque generated, and the combustion region works by triggering the ignition system switch.

B. CNG Dynamic

This system is divided into three items, namely volumetric efficiency values, fuzzy logic, and CNG flow denoted as m_f. The volumetric efficiency value is taken from methane's property value, which moves based on engine speed. Meanwhile, Fuzzy logic is designed with throttle valve position and engine speed input to control CNG based on both attributes. CNG flows to the engine based on speed through the intake of air in the intake manifold. Therefore, the higher the engine speed, the greater the air intake in the manifold and vice versa. Fuzzy logic is a model of the fuel cut-off control system on CNG, which is shown in Fig. 1. The CNG dynamics modeling used in this study is illustrated in Fig. 8.

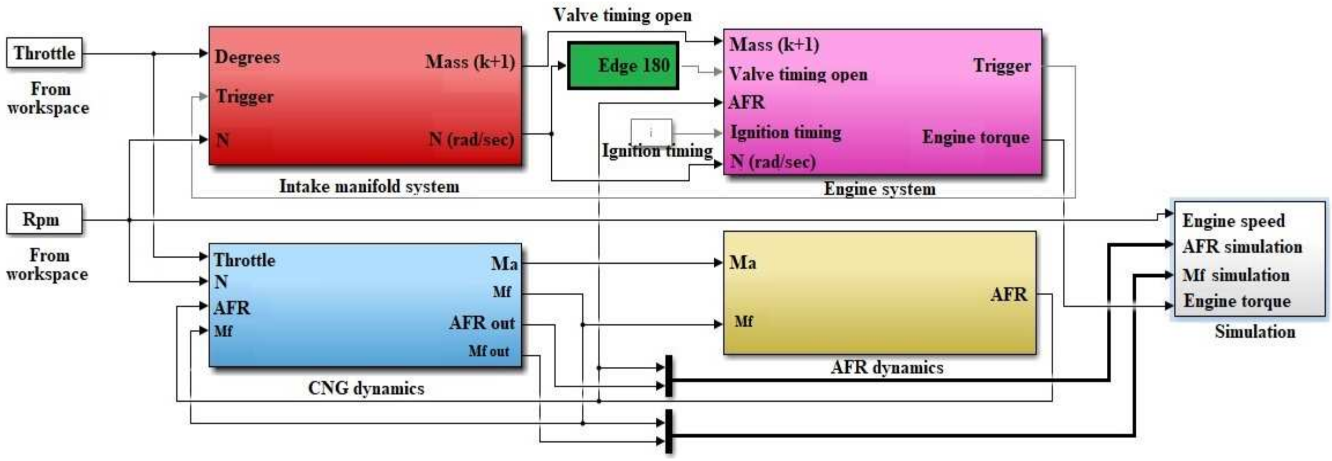

Fig. 7 Engine model with CNG fuel

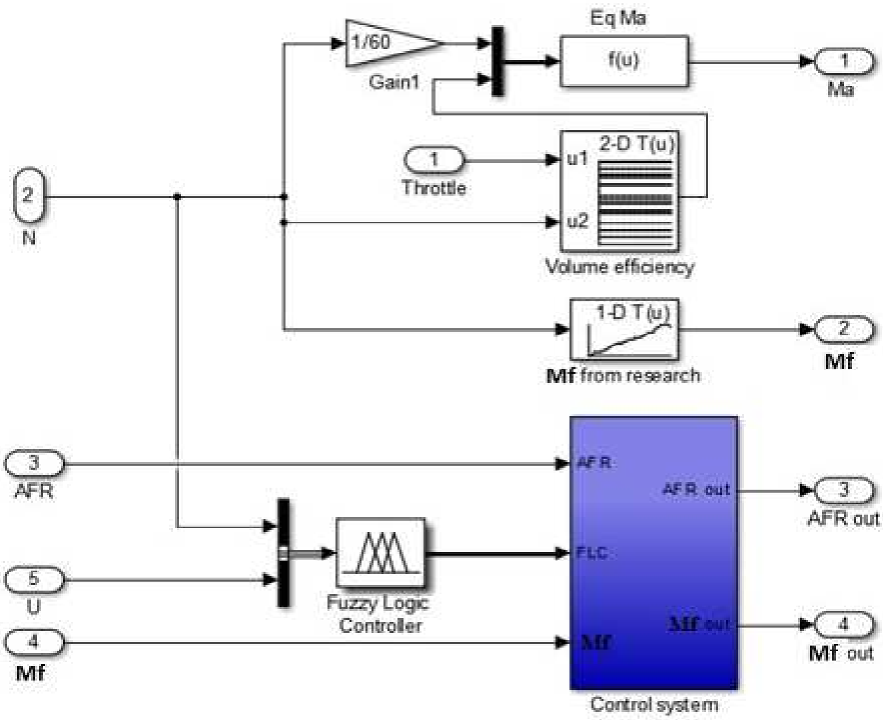

Fig. 8 CNG dynamics model

C. AFR Dynamic

Mixing air and CNG is the key for the engine's operation. AFR dynamics depend on the engine's airflow and CNG flow ratio. AFR dynamics produces a mixture of stoichiometry at various engine speed conditions, as shown in Fig. 9.

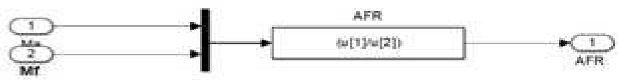

Fig. 9 AFR modeling

D. Intake System

The throttle valve opening angle and the engine speed are inputs to the intake manifold system. The dynamics of the intake manifold system are in the form of negative pressure (vacuum) that occurs due to engine speed and throttle valve opening. Airflow in the intake manifold occurs because the two inputs work in an integrated manner. The intake manifold system modeling is shown in Fig. 10.

E. Engine System

The engine system models the ignition system's generated torque and the triggering process. Meanwhile, ignition works based on the sparks generated by the plug, which are used to ignite the CNG that enters the engine. The torque in the model is affected by the mixture of air with CNG, combustion, and engine speed, as shown in Fig. 11.

F. Throttle Valve Measurement

The throttle valve sensor position and engine speed are measured for 20 seconds. The results are entered in MATLAB Simulink to make the basis for modeling the fuel cut-off. This model is designed to run based on the throttle valve sensor measurement time. In 1-3 and 4 seconds, the throttle valve is opened from an open angle of 10 – 25° and 30°. Meanwhile, in 5 seconds, it begins to close/return to an open angle of 10° and opens again in 6 – 13 seconds at 10 - 25°. Finally, at 14 seconds, it is operated at an open angle of 30° and returns in 15 – 20 seconds at an open-angle position of 10°. The results of measuring the throttle valve position for 20 seconds are shown in Fig. 12.

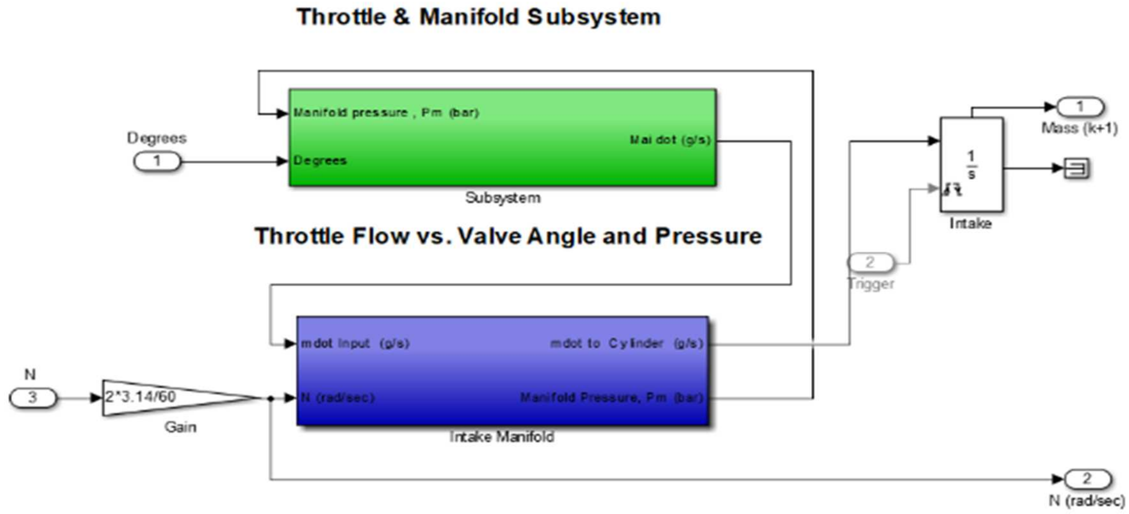

Fig. 10 Airflow model in the intake manifold

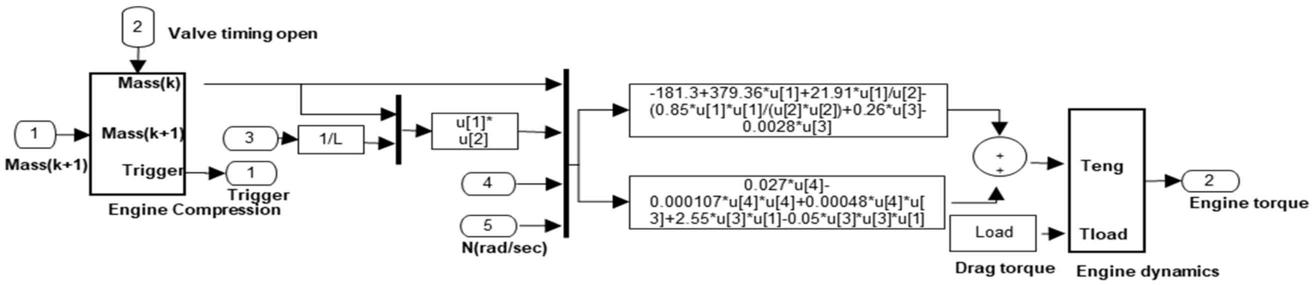

Fig. 11 Engine torque by ignition angle

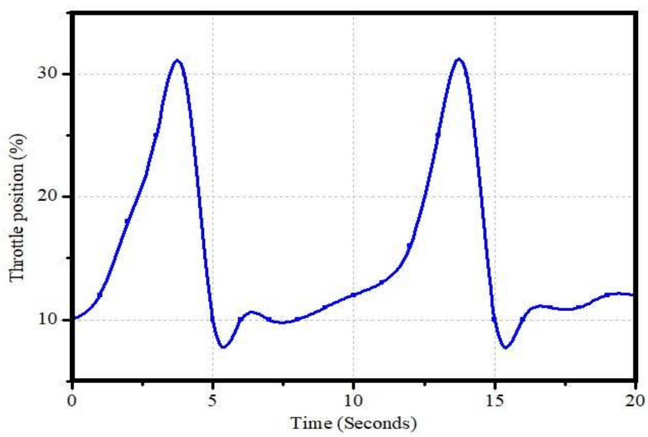

Fig. 12 Result of measuring throttle valve position

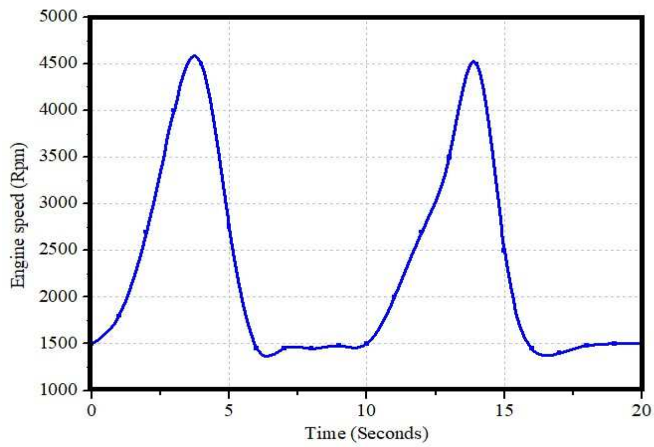

Fig. 13 The results of measuring engine speed from the crankshaft sensor

G. Engine Speed Measurement

The results of the engine speed measurement are illustrated in Fig. 13. Furthermore, the engine is accelerated two times, and at the initial period of 1-3 seconds, it experienced an increase in speed from 1500 - 3500 rev/min. In 4 seconds, it was at its highest rev of around 4500 rev/min. Meanwhile, in 5 seconds, the engine speed starts dropping at 2000 rev/min, and in 6 – 10 seconds, it returns to ± 1500 rev/min. It further increased to 3500 rev/min in 11-13 seconds, with the highest speed of 4500 rev/min obtained in 14 seconds. In 15 – 20 seconds, it fell again in the range of ± 1500 rev/min. This engine speed is captured using real data acquisition.

H. Fuel Cut off Model Simulation

The AFR simulation result on the fuel cut-off controller model designed for CNG engines is shown in Fig. 14. The designed model simulates 2 conditions: simulations with and without fuel cut-off controllers. Models with fuel cut-off work in the following process. In 1-3 seconds, the AFR CNG period 1-3 seconds is in the stoichiometry range (17.2). Meanwhile, in 4-5 seconds, it rose above 20 and returned to stoichiometry in 6-13 seconds. Furthermore, in 14–15 seconds, it re-increased above 20 and returned to the stoichiometry area in 16-20 seconds. AFR CNG engine without fuel cut-off controller only works in the stoichiometry range.

CNG engine with fuel cut-off controller is set during deceleration with an engine speed of 4500 rev/min and throttle valve position at 10° open angle. In this condition, CNG is increased in savings by stopping the flow of fuel to the engine, and the AFR reading more than 20. This area is the result of the system design development. This increase in AFR shows the CNG saving system is working and is a differentiator from previous studies that only operate in the area of stoichiometry (17,2) [20], [28], [29]. Muhssen [20] designed a mixer for mixing CNG with air to make the mixing process more homogeneous. Yang [28] control CNG in the range of AFR 17.2 by considering the stochastic to be more resistant to external disturbances. Wargula [29] observes the impact of a woodchipper machine working on a stoichiometry range. However, these tree studies have not increased CNG savings above the AFR stoichiometric value.

The CNG simulation flow results in the fuel cut-off controller model are shown in Fig. 15. This study models two CNG flows, namely those with and without the fuel cut-off controller. A CNG system without a fuel cut-off controller is modeled as follows. The initial stage of 1 - 3 seconds follows the engine rotation pattern. As the rotation increases, the CNG flow rises, and vice versa. In 4-5 seconds, the flow of CNG decreases following the engine speed. Meanwhile, it increases from 6-13 seconds according to engine speed. Meanwhile, the flow decreases in 14-15 seconds following the engine speed. In 16-20 seconds, the CNG flow returned to its lowest condition.

Its acceleration dynamics conditions have the same flow in a CNG system with a fuel cut-off controller. However, when the deceleration with engine speed is still high and the throttle valve angle is low, the CNG flow to the engine is turned off. CNG with fuel cut-off has a high increase in savings because when the deceleration of the fuel entering the engine is stopped based on fuzzy logic. This can be seen in the simulation results of CNG flow with a fuel cut-off controller from 4-5 and 14-15 seconds, which decreased significantly. The fuel-saving area is the development result of the model system designed in this study.

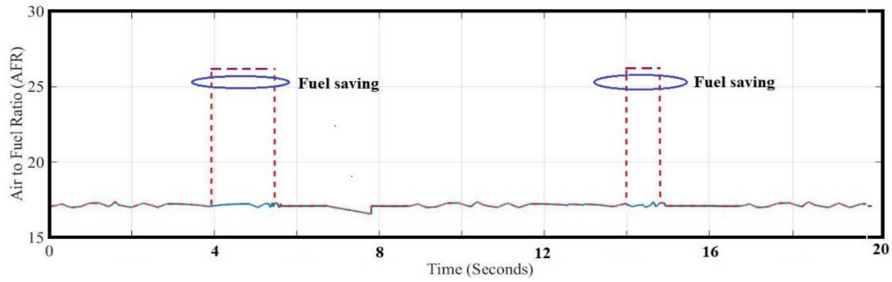

Fig. 14 AFR dynamic

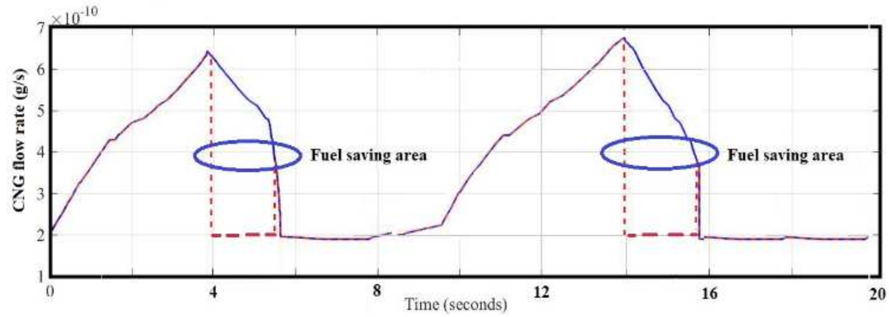

Fig. 15 CNG consumption

IV. Conclusion

The designed CNG engine model has the ability to simulate the controller's conditions with and without fuel cut-off. The designed model has advantages over previous studies which focused on achieving AFR CNG stoichiometry. Therefore, fuzzy logic is used to increase fuel economy by using the fuel cut-off method during deceleration. This method is applied when the throttle valve position is low at a high engine speed. The deceleration condition does not require much power to move the load, thereby saving fuel. CNG savings can be seen from the increase in the AFR value above the stoichiometry (17.2) and the decrease in flow during deceleration. The increase in CNG savings occurred in 4 - 5 and 14 -15 seconds. Its dynamics in entering the engine with the fuel cut controller explain improved fuel economy and have great potential to be applied to real conditions. However, the developed model still occurs within the internal scope of the engine, not considering the vehicle's dynamics when on the highway. Therefore, this condition has the potential to increase fuel economy. The force acting on the vehicle body when operating on the highway can generate kinetic energy, allowing the economizer process in the fuel system.

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