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Development of a transfer function (TF) model for CNG control system design predictions

S Munahar[1*], M Setiyo[2], M M Saudi[3], A Ahmad[3], and B C Purnomo[1]

[1] Department of Automotive Engineering, Universitas Muhammadiyah Magelang, Magelang, Indonesia
[2] Center of Energy for Society and Industry, Universitas Muhammadiyah Magelang, Magelang, Indonesia
[3] Cyber Security and Systems Research Unit, Faculty of Science & Technology, Universiti Sains Islam Malaysia, Negeri Sembilan, Malaysia
*Corresponding author email: munahar@unimma.ac.id

Abstract

Fuel-efficient and environmentally friendly vehicles are currently a priority. Alternative fuels are a smart solution for switching towards vehicle technology that produces cleaner emissions and is, therefore, more environmentally friendly. Compressed Natural Gas (CNG) is a promising alternative fuel because it has more affordable energy prices and is more environmentally friendly. The development of CNG as a fuel-efficient vehicle technology requires a reliable control system. However, the development of this technology has complicated variables that affect its performance. For this reason, before designing a control system, it is necessary to model the system so that it can predict the level of success. This research uses the Transfer Function (TF) modeling approach. TF, as a modeling system, uses Proportional-integral-derivative (PID) as a model for achieving the stoichiometric value (17.2) Air to Fuel Ratio (AFR) CNG the control target system. CNG fuel savings are modeled using mathematical equations with external variables as an economizer system with variable road conditions. The AFR CNG lean value (above stoichiometry) describes the condition of achieving fuel savings under conditions when the economizer system is working. When the economizer system works, system modeling shows an increase in AFR above stoichiometry (18.2). This increase shows that fuel savings have been achieved. This research has not combined ignition time and environmental temperature conditions. Therefore, modeling with this variable is important for future research.

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Keywords

Transfer function model, CNG control system, Proportional-integral-derivative

Introduction

Currently, clean and environmentally friendly energy is an essential need. CNG is an alternative that is starting to be sought because it is cheaper than fossil oil, can work in engines with high compression, and is more environmentally friendly. The increase in fossil prices caused by limited amounts of energy [1][2] and the continuing increase in the number of vehicles [3] is one of the triggers for the world energy crisis. Therefore, as an alternative energy, CNG is a solution to reduce dependence on fossil oil and is more environmentally friendly. CNG is starting to be used as vehicle fuel because it has sufficient properties. Research on CNG as combustion energy for vehicle engines is developing with several themes, including injection systems, ignition systems, application of EGR, mixing CNG to improve combustion quality, designing modeling systems, and controlling CNG mixing methods.

The CNG injection system method is starting to be developed because it has better efficiency effects. Yuvenda et al. [4] tried to use a Pulse Width Modulation (PWM) system to control the CNG injection time. Meanwhile, Nguyen et al. [5] tried to develop a form of CNG spraying in the combustion chamber. This research examines how injection control can improve combustion performance. However, the aspect of the mixture between air and fuel, known as the air-to-fuel ratio (AFR), has yet to be carried out in this research.

The AFR method is becoming the center of attention of researchers because it increases engine performance and better fuel efficiency. Kar et al. [7] and Muhssen et al. [6] use AFR stoichiometry as the main approach in their research. Efficiency is quite satisfactory in the AFR range of 17.2 – 17.4. However, this study has not discussed the application of AFR lean (above AFR stoichiometry).

Engine performance is not only controlled by AFR, but the ignition system for CNG combustion is quite influential. Researchers began to introduce laser methods for burning CNG [8]. Intelligent Dual Sequential, or IDS, ignites the spark plugs to reduce emissions when the engine enters the exhaust cycle [9]. This research observes reduced emissions because the engine flushing effect can be suppressed. Other research uses the multiplexed extreme method to calibrate CNG technology to increase engine power [10]. These three studies examined how the CNG combustion system can control engine power. However, the fuel-saving aspect has yet to be the focus of the research.

Exhaust Gas Recirculation, abbreviated as EGR, really helps reduce engine temperature, which reduces NOx gas, which continues to be developed [11]. This research uses the Particle Number (PN) method in exhaust gas content to observe Nox gas. Kontses et al. [12] tried to compare PN from burning CNG with other fuels. There is other application research that is more interesting to discuss, namely changes in driving behavior [13][14]. This research examines the relationship between driving behavior and the emissions produced. However, these three studies have not yet examined the aspect of CNG fuel savings.

The combination of RCCI and CNG combustion methods is starting to be implemented [15]. Increasing engine performance by modifying the compression ratio is an interesting potential to discuss because CNG has a high-octane number [16]. The result is a positive relationship between the compression ratio of the CNG engine and the engine power produced. Both studies are oriented toward the most optimal combustion modification to increase engine power, but fuel savings have yet to be discussed.

Modeling development is necessary to determine CNG systems' optimization in research. CNG fluid dynamics simulations are interesting to discuss using Computational Fluid Dynamics - CFD Software. Sadah et al. [17] simulated mixing air with CNG using the dynamics system in CFD. Meanwhile [9] observed torque changes in CNG engines using a dual sequential ignition system. Both studies discuss integrated CNG modeling, but fuel savings have yet to be observed. Looking at the development of CNG research, several themes have yet to be discussed, including increasing fuel economy, transfer function modeling, injection systems using the direction method, and others. In developing CNG as a material-saving vehicle technology, vehicles need a reliable control system. However, the development of this technology has complicated variables that affect its performance. Based on these conditions, before designing a control system, it is necessary to model the system to predict the success level. For this reason, this research aims to develop a CNG system modeling to increase fuel economy by using a function transfer approach to a direct injection system with variable road conditions. This fuel system concept is that CNG is sprayed in the combustion chamber, requiring a fuel pump (3), which refers to Figure 1. CNG is stored in a tube (1), which flows to the fuel pump [18] (3) and is regulated by a solenoid valve (2). The CNG entering the engine (7) is regulated by the injector (4) via the Engine Control Unit -ECU command (8). The ECU (8) in regulating the CNG flow works based on input from the throttle position sensor (9), engine speed sensor (6), manifold absolute pressure sensor (5), and angle sensor (10).

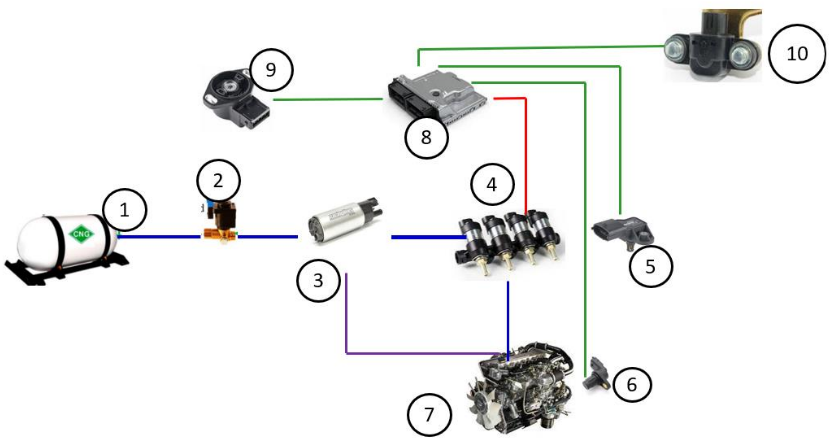

Figure 1. The system concept is the reference for developing the transfer function

Methods

Transfer function and control system block diagram

This research designs a transfer function model for the control system shown in Figure 2. The transfer function is a mathematical modelling obtained from a comparative analysis of input-output functions. This input-output function comes from experimental data, which is processed using MATLAB's ident function (the state space part). This mathematical modelling has two block diagrams, block diagram A and block diagram B, which were designed with MATLAB Simulink software. Block diagram A is designed as a transfer function for a closed-loop control system, referring to references from MathWorks [19]. Block B diagram is an economizer modelling designed with variable engine speed and road slope.

Block diagram

The block diagram A in Figure 2 is a mathematical model of the AFR control system on a vehicle with a set point value of 17.2. This block diagram comprises Proportional-Integral-Derivative (PID) and fuel system transfer functions. PID is an AFR control controller that describes the achievement of stoichiometry values in the fuel system. The fuel system transfer function models the fuel pump and injector system. The fuel pump consists of an electric motor and a centrifugal pump unit.

Mathematical model of pump electric motor

The electric motor is a component that produces power, which is used to move fuel. This electric motor has a transfer function, which is shown in Equation 2.1 [20]. Where, T_L is the mechanical time constant of an electric motor with a value of 0.012 seconds, T_S is denoted as the electrical time constant of an electric motor with a value of 0.002 seconds, and k_L is the motor gain factor, which has a value of =1.

$$\mathrm{G(s)} = \frac{k_L}{(T_L s+1)((T_S s+1)} \qquad (1)$$

Mathematical model of centrifugal pump unit

A centrifugal pump unit is a pump that works using an impeller to move liquid based on centrifugal force. This centrifugal pump unit has quite complicated working conditions. For this reason, in describing the mathematical model of centrifugal pumps, several assumptions are made, including that centrifugal pump pulses are ignored, centrifugal pump leaks are ignored, and dynamic processes of centrifugal pumps are ignored. The steady-state gain transfer function of the centrifugal pump unit is obtained by comparing the Q value (fuel flow) and the centrifugal pump rotation with the notation n shown in Equation 2.2. The transfer function of a centrifugal pump unit has a value of k. According to [21] if the fuel flow (Q) of a centrifugal pump is proportional to the speed of the centrifugal pump, then the value of k = 1.

$$G(s) = \frac{Q}{n} = k \qquad (2)$$

Injector mathematical model

The injector is a component used to inject fuel into the engine. This component has a transfer function shown in Equation 2.3. Steady-state gain of the injector transfer function is obtained by comparing the Q value (fuel flow in milliliters/second) with the

Pulse With Modulation (PWM) frequency – f in Hz units to control the fuel. Real vehicle fuel flow under stoichiometry conditions is at ± 0.00113 liters/second = 1.113 milliliters/second. The PWM on the injector from measurements on real vehicles has an on/off value of 5 milliseconds so that in one cycle, it has a value of 10 milliseconds, so the injector works in one second having a frequency of 100 cycles = 100 Hz. k_i functioned as an injector gain factor.

$$G(s) = \frac{Q}{f} = k_i \qquad (3)$$

Mathematical models of fuel systems

The mathematical model of the material system is obtained from the integration between Equation 2.1, Equation 2.2, and Equation 2.3, shown in Equation 2.4. The fuel system transfer function integrates these three equations designed in MATLAB Simulink.

$$G(s) = \frac{k \times k_L \times k_i}{(T_L s+1)((T_S s+1)} = \frac{0{,}0113}{0{,}00024s^2+0{,}014s+1} \qquad (4)$$

The gain with a value of 100 in Figure 2 is connected before the steady state gain of the fuel system transfer plant function with a closed loop system, which is used to model AFR control, the results of which provide feedback to the PID control. The first block diagram (A) shown in Figure 2 as a control system in the test vehicle has an AFR value in the stoichiometry range (17.2). Achieving AFR stoichiometry is an operational target to increase engine performance to make it more optimal. However, this achievement has other factors that are ignored, so it has shortcomings that cannot be avoided in certain conditions.

Results and Discussion

The results of the CNG fuel system transfer function design is presented in Figure 2. This transfer function is a replacement equation function for the designed control system. This system has block diagrams A and B. Block B is considered a system for increasing fuel economy based on two inputs, namely engine speed and angle sensor.

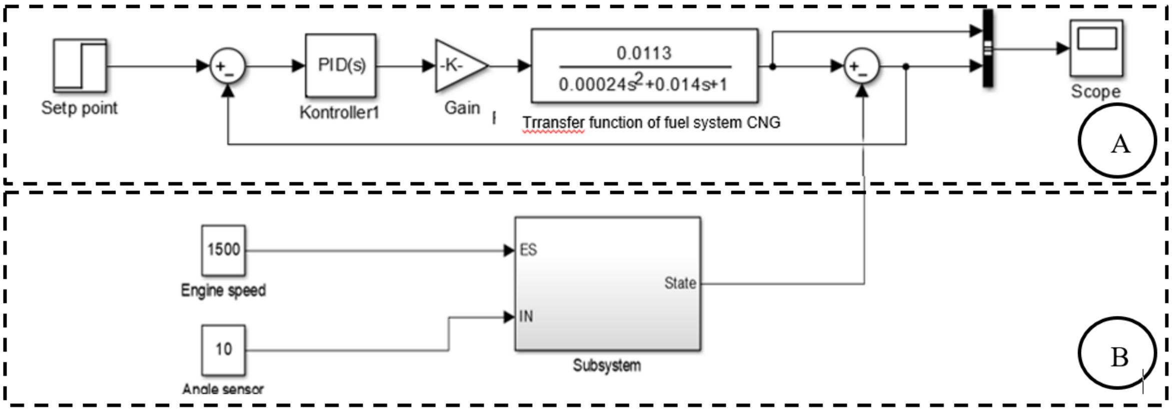

Figure 2. CNG control system transfer function block diagram

The transfer function system designed is a replacement equation for the AFR CNG control system. The CNG fuel-saving system works based on the controller mapping, which refers to Table 1. The fuel-saving system function works when the engine speed and the angle sensor are high. Engine speed and angle sensor are clustered into two conditions: low has a range of 700 – 1800 rotations per minute (rpm), and high has a range above 1800 rpm. Angle sensors, namely low, have a range of 0 - 5° and high have a range above 5°.

Table 1. Mapping of CNG saving system

No.	Description	Engine speed	Angle sensor	Fuel savings
1.	Vehicle position on a flat road	1	1	A
2.	Vehicle position on a flat road	1	2	A
3.	Vehicle position on a flat road	2	2	A
4.	Vehicle position on a flat road	1	1	A
5.	Vehicle position on a flat road	1	2	A
6.	Vehicle position on a flat road	2	1	A
7.	Vehicle position on a flat road	2	2	B

Note: 1= low, 2= high, A= the savings system doesn't work, B= the savings system work.

The CNG fuel system transfer function design was made using MATLAB Simulink, presented in Figure 2, and the results are in Figure 3. The results of the fuel system transfer function simulation are the dynamics of AFR CNG. When the engine speed and angle sensor conditions are in the high fuel position, the fuel is reduced, and it can be seen that AFR CNG has a higher value. Figure 3 shows the system dynamics of the CNG control system response. This response system has several conditions: rise time, steady state error, overshoot, peak team, and settling time.

The CNG control system, when not using a fuel-saving system, has a rise time of 1 second, steady state error of 3.5 seconds, overshoot of 18, peak time of 1.8 seconds, and settling time of 4 seconds. The dynamics of AFR CNG are in the stoichiometry range of 17.2. Meanwhile, the CNG control system, when using a fuel-saving system, has a rise time of 1 second, steady state error of 3.5 seconds, overshoot of 18, peak time of 1.8 seconds, and settling time of 4 seconds. The dynamics of AFR CNG are in the stoichiometry range of 18.2. The increase in savings occurred as seen from the increase in AFR CNG.

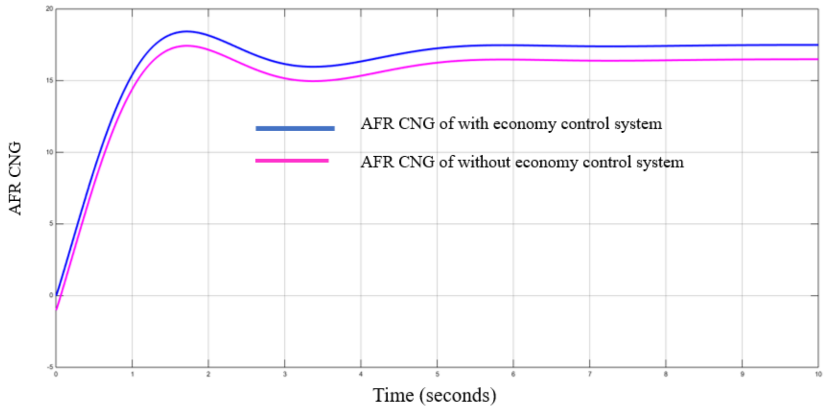

Figure 3. Dynamics of AFR CNG in the development of the transfer function of the CNG control system

The transfer function system for the CNG fuel system that has been created has two conditions. The CNG control system, when not using a fuel-saving system, confirms previous research that discussed AFR CNG in the stoichiometry range [6]. However, when the CNG control system uses a fuel-saving system, it is an advantage of research carried out by previous researchers [7] in terms of increasing fuel savings. Model research on CNG generally focuses on discussing the process [22][23] and does not discuss the system response. The advantage of the research is that it discusses the dynamics of the system response to CNG dynamics based on achieving control system targets.

Conclusion

CNG system modeling to increase fuel economy using a function transfer approach has been designed. This modeling can simulate fuel savings with AFR CNG dynamics when using and without a fuel-saving system. When the fuel-saving system works with a road slope angle above 5°, the AFR CNG is above the AFR Stoichiometry value (18.2). However, when the fuel-saving system is not working (the road slope angle is below 5°), the AFR CNG is in the stoichiometry range (17.2). Savings are shown by the increase in AFR from 17.2 to 18.2. The AFR 18.2 engine is in safe condition. Seeing these conditions, a CNG control system with fuel savings has the potential to be applied in real conditions. This research has not combined ignition time and environmental temperature conditions. Therefore, modeling with this variable is important for future research.

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