Setiyo et al. 2017. *Int. J. Vehicle Structures & Systems*, 9(4), 261-265
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi: 10.4273/ijvss.9.4.12

International Journal of
Vehicle Structures & Systems
Available online at www.maftree.org/eja

Modeling of Deceleration Fuel Cut-off for LPG Fuelled Engine using Fuzzy Logic Controller

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ABSTRACT:

At the time of deceleration, continuous LPG flow in LPG fuelled engine causing over fuel consumption and increasing exhaust emissions, while the engine does not need fuel. Therefore, this paper presents a simulation of deceleration fuel cut-off (DFCO) system. Given that the fuel system control is complex and non-linear, modeling with fuzzy logic controller (FLC) has been selected because of simple, easy to understand and tolerant to improper data. The engine modeling is divided into several sections, including intake manifold dynamics and engine dynamics. The input values were processed by the membership function. A series of simulation results indicate that DFCO can be applied. The combination of throttle valve position, engine speed and manifold pressure is able to cut LPG flow at deceleration. As a conclusion, DFCO system is promising to be applied on LPG-fuelled vehicles for saving fuel and reducing emissions.

KEYWORDS:

LPG fuelled engine; Deceleration; deceleration fuel cut-off; Air to fuel ratio

CITATION:

M. Setiyo, S. Munahar, A. Triwiyatno and J.D. Setiawan. 2017. Modeling of Deceleration Fuel Cut-off for LPG Fuelled Engine using Fuzzy Logic Controller, *Int. J. Vehicle Structures & Systems*, 9(4), 261-265. doi:10.4273/ijvss.9.4.12.

1. Introduction

During the last decade, declining air quality, especially in urban areas has become a serious concern because it directly impacts on human health [1]. The transport sector becomes a major contributor to the increasing air pollutant emissions and global greenhouse gas [2]. Most countries now have implemented policies of fuel economy standards for road vehicles as an effective way to reduce oil consumption, carbon emissions and air pollutants. The internal combustion engine technology is also evolving in that direction [3-5]. Therefore, this paper presents a simulation of cut-off the fuel flow during deceleration in the LPG fuelled engine as an effort to reduce fuel consumption and emissions. The use of alternative fuels such as LPG, ethanol, methanol, DME and hydrogen is one form of energy policy taken by many countries. LPG becomes an option because it can be directly accepted on the existing vehicle technology only by adding a converter kits on the fuel system [6]. Although less promising in terms of power output [7-9], but the exhaust emissions from LPG engines are cleaner than gasoline engines [10-12].

LPG also is an option in some countries because they are able to compete with conventional fuels [13]. Now-a-days, LPG vehicle technology is equaled to gasoline direct injection (GDI), wherein the liquid LPG is injected directly into the combustion chamber through the technology of direct injection liquid phase (LPDI). However, the converter and the mixer models is still the most widely used, especially in old vehicles that are modified to LPG experience [14]. Generally, LPG vehicles are used in bi-fuel systems that its can run on gasoline and LPG mode alternately. The basic scheme of bi-fuel engine is presented in Fig. 1.

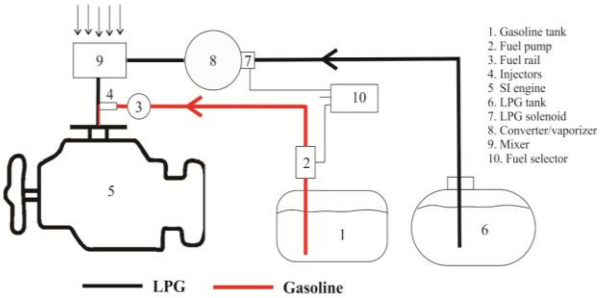

Fig. 1: Basic schematic of bi-fuel LPG/gasoline engine using the converter and mixer LPG kit [15]

In recent decades, many approaches have been made to improve the fuel economy of the engine LPG. As it is known that a stoichiometric mixture ($\lambda = 1$) can achieve good thermal efficiency [16]. Recently, an LPG temperature control system to improve emission of LPG fuelled vehicles has been developed. The flow rate of cooling circuit in the vaporizer is controlled by a valve that is activated by PID controller unit. The results showed that NO emissions can be decreased by about 2% compared with operation with original LPG injection system [17]. In addition, the application of control systems, emissions of LPG vehicles can be reduced far below the gasoline operation [18].

In the converter and mixer LPG kit, LPG sucked into the engine is regulated through a vacuum in the intake manifold. At the time of deceleration, intake manifold vacuum is great because the throttle valve is closed. This causes wastage of fuel and produces high emissions. The alternative way to save fuel as well as to reduce emissions is by stopping the LPG flow when the engine is on deceleration through the fuel cut-off the system [19-20]. In the fact that the internal combustion engine has a complex dynamic system, including the relationship between fuel flow, engine speed, combustion and exhaust gas flow, the best way to drive a fuel cut-off system is by a control system. In this study, the deceleration fuel cut-off (DFCO) was modeled by a computer simulation to drive the solenoid on LPG converter. Given that the system in the vehicle is dynamic and non-linear [21-25], the approach taken in this modeling is by the fuzzy logic controller (FLC). FLC was chosen because it has relatively good system stability, able to resolving the black box problem and can be applied on a multi input multi output (MIMO) [26]. Fuzzy mathematical concepts are very simple and easy to understand. Fuzzy is also tolerant of data improper.

2. System modeling

In this study, a mathematic model is used for modeling the actual condition of the SI engine. The engine modeling is divided into several sections, including intake manifold dynamics and engine dynamics [27-28]. The relationship between manifold air pressure, manifold air temperature, crankshaft speed dynamics and fuel dynamics is presented in Fig. 2.

2.1. Intake manifold dynamics

Intake manifold dynamics are influenced by the position of the throttle valve, intake manifold pressure and air mass flow rate. Intake manifold dynamics is presented in Eqn. (1) as follows

$$\dot{m}_{ai} = f(\theta) \cdot g(P_m) \tag{1}$$

Where $\dot{m}_{ai}$ is the air mass flow rate into manifold (g/s). θ is the throttle valve position in degree. P_m is intake manifold pressure (bar). Constraints on the intake manifold dynamics are given in equation 2-6 as follows.

$$f(\theta) = 2.821 - 0.05231.\theta + 0.10299.\theta^2 - 0.00036.\theta^3 \tag{2}$$

$$g(P_m) = 1;\ if\ \ P_m \leq \frac{P_{amb}}{2} \tag{3}$$

$$g(P_m) = \frac{2}{P_{amb}}\sqrt{P_m.P_{amb-}P^2{}_m};\ \text{if}\ \frac{P_{amb}}{2} \leq P_m \leq P_{amb} \tag{4}$$

$$g(P_m) = -\frac{2}{P_{amb}}\sqrt{P_m.P_{amb-}P^2{}_{amb}};\ \text{if}\ P_{amb} \leq P_m \leq P_{amb} \tag{5}$$

$$g(P_m) = -1;\ if\ P_m \geq P_{amb} \tag{6}$$

In fact, when the engine is running, there would be changes in the intake manifold pressure. In this case, the air mass over time in the intake manifold is the difference in mass flow rate incoming and outcoming without considering the engine gas recirculation (EGR). The change in pressure in the intake manifold is presented in Eqn. (7) as follows

$$\dot{P}_m = \frac{R \cdot T}{V_m}(\dot{m}_{ai} - \dot{m}_{ao}) \tag{7}$$

$$\dot{m}_{ao} = -0.366 + 0.08979 \cdot N \cdot P_m - 0.0337 \cdot N \cdot P_m{}^2 + 0.0001 \cdot N^2 \cdot P_m \tag{8}$$

Where $\dot{P}_m$ is the intake manifold pressure changes (bar/s). R and T are the gas constant and air temperature (K), respectively. Meanwhile, V_m is the intake manifold volume (m^3) and $\dot{m}_{ao}$ is the air mass flow rate out of the intake manifold (g/s). Finally, N is the angular engine speed (rad/s).

2.2. Engine dynamics

It is known, the engine torque is influenced by the mass of air entering the cylinder, air to fuel ratio, ignition timing and the engine speed. Torque computation is expressed by Eqn. (9).

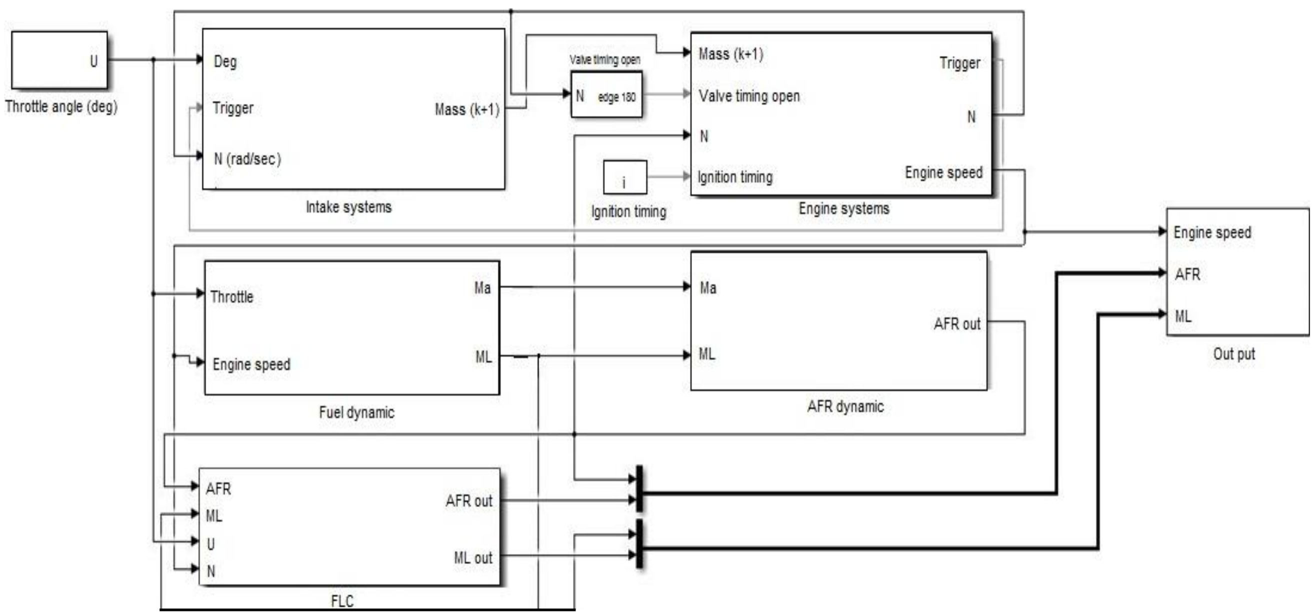

Fig. 2: Engine modeling

$$Torque_{eng} = -181.3 + 379.36.m_a + 21.91.AFR - 0.85.AFR^2 + 0.26.\sigma - 0.0028.\sigma^2 + 0.027.N - 0.000107.N^2 + 0.00048.N.\sigma + 2.55.\sigma.m_a - 0.05.\sigma^2.m_a \quad (9)$$

Where $Torque_{eng}$ is the torque generated by engine (N.m). AFR is the air to fuel ratio sucked into the cylinder. σ is the spark advance before top dead center (degree) at compression stroke. Then, the angular engine acceleration is expressed using equation (10) as follows,

$$JN = Torque_{eng} - Torque_{load} \quad (10)$$

2.3. LPG flow rate

In this study, LPG is applied on 1998 cc of bi-fuel engine experience. LPG is sucked into the engine based on the intake manifold vacuum. Referring to Fig. 1, LPG is flowing from the evaporator and mixed with air in the mixer device. The flow rate of air mass depends on engine displacement, volumetric efficiency, air density, and engine speed. The amount of air entering the engine is calculated by Eqn. 11 as follows

$$m_a = \frac{\eta_v \cdot \rho_a \cdot V_d \cdot N}{12 \cdot 10^7} \quad (11)$$

Where m_a is air mass sucked into the cylinder (g/s). η_v, ρ_a, V_d, N are the volumetric efficiency, air density (kg/m^3), engine displacement (m^3) and engine rotation (rev/min), respectively. In this study, the density of the air entering the cylinder is assumed constant at 1.2 kg / m^3. Meanwhile, the volumetric efficiency is calculated from Masi study [7]. Referring to Table 1 and Eqn. 11, the LPG flow rate and AFR through the engine speed can be calculated using Eqns. 12 and 13 respectively.

$$m_L = \frac{m_a}{AFR} \quad (12)$$

$$AFR = \frac{m_a}{m_L} \quad (13)$$

Table 1: Volumetric efficiency of 1998 cc LPG engine

Engine speed, n (rev/min)	Volumetric efficiency, η_v	Engine speed, n (rev/min)	Volumetric efficiency, η_v
1000	0,720	3600	0,747
1200	0,740	3800	0,743
1400	0,755	4000	0,742
1600	0,771	4200	0,747
1800	0,789	4400	0,755
2000	0,805	4600	0,764
2200	0,817	4800	0,779
2400	0,824	5000	0,792
2600	0,820	5200	0,790
2800	0,803	5400	0,775
3000	0,782	5600	0,750
3200	0,766	5800	0,710
3400	0,755	6000	0,650

2.4. DFCO modeling

DFCO modeling present fuel control system developed. Fuel cut-off system works based on the response of the throttle valve u and engine speed N. DFCO modeling is presented in Fig. 3. DFCO is active when the engine speed is high while the position of the throttle valve is small. In this condition, the engine does not need fuel. DFCO that developed this work based on the decision presented in Table 2.

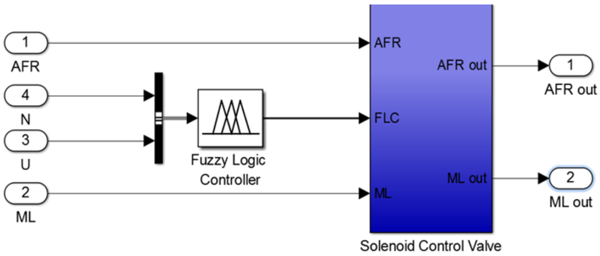

Fig. 3: Deceleration fuel cut-off (DFCO) modeling

Table 2: DFCO decision

Throttle valve position	Engine speed	DFCO decision
High (47 - 100%)	High(3128 - 6000 rpm)	off
High (47 - 100%)	Medium (2200 - 3730 rpm)	off
High (47 - 100%)	Low (0 - 2700 rpm)	off
Medium (8 - 55%)	High (3128 - 6000 rpm)	off
Medium (8 - 55%)	Medium (2200 - 3730 rpm)	off
Medium (8 - 55%)	Low (0 - 2700 rpm)	off
Small (0 - 15%)	High (3128 - 6000 rpm)	on
Small (0 - 15%)	Medium (2200 - 3730 rpm)	off
Small (0 - 15%)	Low (0 - 2700 rpm)	off

2.5. Membership function

Fuzzy logic controller (FLC) requires the value of membership function (MF) as an input. MF is a curve that shows the points mapping of input data into membership values (degree of membership) which have the interval between 0 and 1. In this study, MF is designed for two-input, MF of the throttle valve position and the MF of engine speed, respectively. Firstly, MF of the throttle valve is divided into three grades of membership, small, medium and big. MF value for small, medium and big is 0 - 15%, 8% - 55% and 45% - 100%, respectively. Throttle valve dynamics in MF are presented in Fig. 4. Secondly, MF of engine speed also consists of low, medium and high. MF values of low, medium and high are 0 - 2700 rpm, 2300 rpm up to 3700 rpm and 3200 rpm - 6000 rpm, respectively. MF of engine speed is presented in Fig. 5. Therefore, FLC will provide a digital signal to regulate electric voltage to the solenoid mounted on LPG vaporizer.

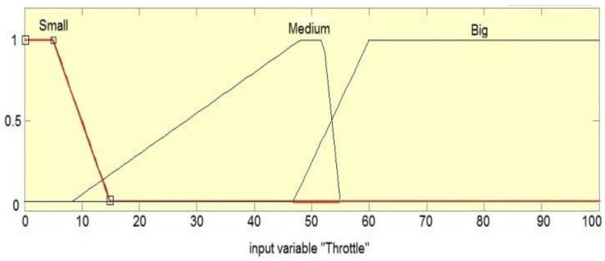

Fig. 4: Membership function (MF) of throttle valve position

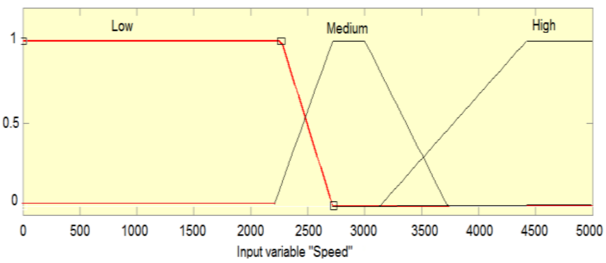

Fig. 5: Membership function (MF) of engine speed

3. Results and discussion

3.1. Input condition

In this study, the engine is simulated for 10 seconds which represents an acceleration and deceleration. Referring to Fig. 1 and 3, the main input of the engine is a throttle valve position. The first period 0 seconds, the throttle valve is opened 13%. The second period from 0 - 2 second, the throttle valve is linear opened from 13% - 23%. The third period exactly at 2 seconds, the throttle valve is closed from 23% - 5%. The third period is kept up to 10 seconds. Dynamics of throttle valve position is presented in Fig. 6.

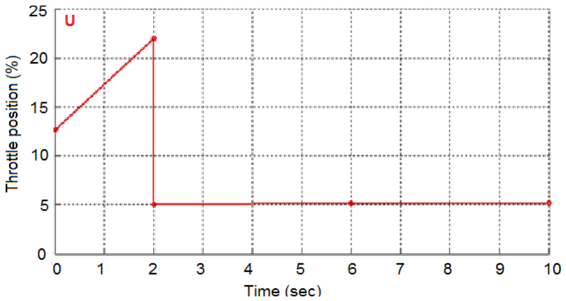

Fig. 6: Simulation of throttle valve position from 0 to 10 seconds

3.2. Effect throttle valve position on engine speed

It is known, when the throttle valve is opened, the air and fuel are sucked into the cylinder. Combustion pressure will generate engine speed. Noting the equation (1-13) was processed by FLC, results of engine speed (with throttle valve position according to Fig. 6) is presented in Fig. 7. Throttle valve opened from 13% - 23% increasing the engine speed from 2000 rev/min - 5300 rev/min. Then, when the throttle is closed abruptly 2 seconds, engine speed stays high until 4 seconds. The engine still operated at high speed even though the throttle valve closes. In this condition, the fuel flowing into the cylinder, though not required.

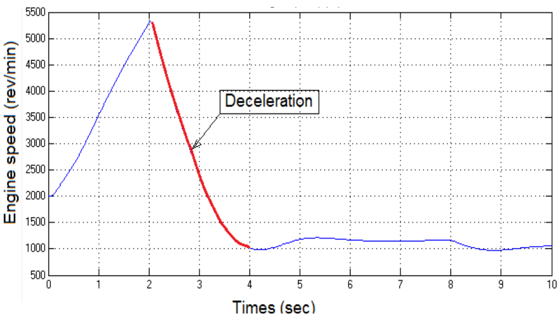

Fig. 7: Engine speed simulation based on throttle valve dynamics

3.3. Fuel cut-off conditions

DFCO performance can be seen by AFR curve shown in Fig. 8. When the engine is acceleration (a-b), the dynamics of the intake manifold pressure causes the AFR fluctuate. Then, when the throttle valve is closed suddenly (b-c), AFR reads very high undetected value. This condition indicates DFCO are working. LPG flowing to the engine is disconnected by the solenoid. FLC re-activate solenoid some time before the engine turns on the target determined (c-d). Subsequently, if the throttle valve is opened constant, AFR also is legible constant (d-e).

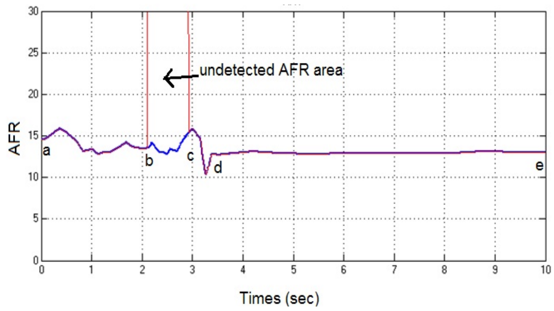

Fig. 8: DFCO performance

3.4. Fuel consumption

In accordance with the objectives of this study, DFCO is used to reduce fuel consumption and to reduce emissions. Therefore, the performance of DFCO against fuel savings and emission reductions are presented in Fig. 9. When the engine operates from 0 - 2 seconds period, consumption of LPG has increased. At the time of DFCO active, fuel consumption read in 0 g/s. Blue line present LPG consumption without DFCO control system and purple line present LPG consumption with DFCO control system.

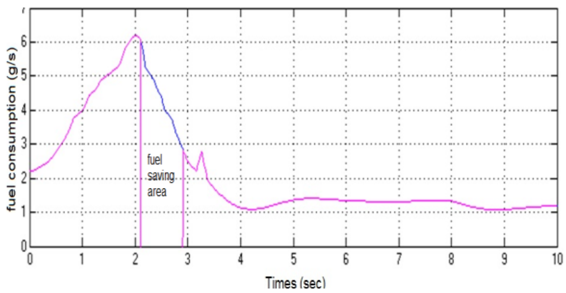

Fig. 9: Effect DFCO on fuel consumption

4. Conclusion

A series of simulation results indicate that modeling FLC to cut-off the LPG flow during deceleration which is a non-linear condition can be applied. The throttle valve position, engine speed and manifold pressure were able to control the LPG flow in the desired condition. At the time of deceleration, AFR is undetected, which means there is no LPG flow from fuel line into the engine. In conclusion, DFCO system is a promising to be applied on LPG fuelled vehicles for fuel saving.

ACKNOWLEDGEMENTS:

This research is fully supported by Automotive laboratory of Muhammadiyah University of Magelang and electrical laboratory of Diponegoro University. The researchers are grateful to both institutions.

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