Research Article

Design and application of air to fuel ratio controller for LPG fueled vehicles at typical down-way

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Received: 5 August 2019 / Accepted: 3 December 2019

Abstract
This article presents an investigation of air–fuel ratio (AFR) controllers applied to liquefied petroleum gas (LPG) fuelled vehicles with second-generation LPG kits. When a vehicle is running on a down-way, fuel consumption tends to be rich because of the increased vacuum in the intake manifold. Therefore, an AFR controller was developed that can work based on a vehicle's tilt sensor combined with an oxygen sensor. AFR controllers are employed to regulate injectors to form leaner mixtures. We tested the performance of AFR controller at a typical down-way of 10°, 15°, and 20°. As a result, the AFR controller was able to increase AFR value from an average of 14.5 (without controller) to 15.5–16.2, depending on the gear position and down-way angle. Furthermore, a greater of road slope was observed to have produced greater AFR. This AFR controller is very promising to be applied to vehicles operating in mountainous areas.

Keywords LPG vehicle · AFR controller · Down-way

1 Introduction

In the past few decades, environmental factors have become the main orientation in technological development, especially concerning health issues. In addition to the industrial sector, transportation is one of the sectors targeted to reduce global warming, air pollution and emissions [1–3]. Therefore, the design of vehicle technology needs to consider emission factors [4, 5]. From another perspective, there is also a potential global energy crisis and this call for the design of technology to improve fuel efficiency for new and operating vehicles [6].

Electric vehicles (EVs) and Fuel Cell Vehicles (FCVs) are very promising to reduce fuel consumption and emissions, even to zero value, in the future. However, the implementation of EVs and FCVs is constrained in developing countries due to uncompetitive prices and limited mileage [7]. In EVs, the battery requires a long time to charge with high input power [8] while FCV is limited by infrastructure needed to produce hydrogen. In the medium term, hybrid vehicle (HVs) is a reasonable choice and it involves combining internal combustion engines (gasoline/diesel) with electric motors [8, 9]. However, this technology is also not yet widely accepted due to the relatively high total cost of ownership (TCO).

Therefore, in the short term, controlling air to fuel ratio (AFR) is an alternative method to reduce fuel consumption and emissions. This system has progressed rapidly, even with the use of proportional–integral–derivative (PID) for stoichiometric purpose [10]. Neural networks as intelligent control systems have also been applied to control AFR with the concept of brain tissue [11]. Several other studies have been conducted by processing signals generated by oxygen sensors [12], applying genetic algorithms [13], fuzzy logic controllers (FLC) [14–16], diagonal recurrent neural network (DRNN) [17], and brakes control system [18].

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SN Applied Sciences (2020) 2:37 | https://doi.org/10.1007/s42452-019-1839-8

Published online: 06 December 2019

Moreover, other methods to reduce emissions have been researched to include the application of alternative fuels such as ethanol, methanol, compressed natural gas (CNG), and LPG [19, 20]. Ethanol produces good efficiency and reduces emissions, but it cannot be produced in large numbers except a country has a reliable policy on agricultural land for food and energy [21]. Therefore, LPG is considered an alternative and choice of several countries due to many advantages such as high octane, lower exhaust emissions, and availability.

Research on several variables of LPG as an alternative fuel has been conducted by different researchers. For example, Morganti [22] conducted a study to test the research octane number (RON) and motor octane numbers (MON) for iso-butane, propylene, *n*-butane and propane, followed by observations of auto-ignition from a mixture of propane and butane. In another study, Chikhi [23] investigated CO, HC, NOx and CO_2 emissions produced by 17 units of bi-fuel vehicle using LPG to replace gasoline and diesel. Moreover, it is also possible to control the sulfur and toxic gases produced by LPG vehicles to achieve better emissions [24, 25]. Other studies focus on iso-octane and air mixtures [26], performance characteristics of LPG, CNG and LNG vehicles [27], direct-injection application with lean combustion methods [28], and risk analysis of the safety of LPG-fueled cars [29].

Meanwhile, several research works have also been conducted on the control of LPG. In 2015, Erkus [30] developed an LPG control system to be applied in carburetor-based engines. The results of this study confirm an increase in engine performance and better exhaust emissions compared to the carburetor system. Others study, including the fuel cut-off method to cut off LPG flow to the engine during deceleration by controlling the solenoid on the vaporizer [31, 32], emission comparison using a control system on liquid phase injection (LPI) and direct injection (DI) [33], as well as the characteristics of injection duration and control [34–36]. This has led to the development of intelligent control systems to support fuel efficiency. However, the studies conducted have not considered the contours of the land, such as up-way and down-way. When a vehicle passes through a down-way, kinetic force, and gravity affect its movement. Meanwhile, when the vehicle accelerates on a down-way, the fuel is reduced or even cut off.

Furthermore, even though LPG kits technology is now equal to GDI technology, in fact, more LPG vehicles use second-generation LPG kits (vapor phase injection, VPI) without strict AFR and emission settings [37]. With second-generation LPG kits, AFR stoichiometry is only obtained in partial conditions. When the vehicle accelerates in the down-way, the tendency for low AFR is greater than the high AFR. Therefore, we developed the AFR control system on LPG vehicles that pay attention to the slope of the road. This control system works based on the primary information from the tilt sensor.

Table 1 Vehicle specification

Descriptions	Specification
Engine manufacturer	Toyota
Engine code	5A-FE
Cylinders	Inline 4
Capacity	1498 cc
Bore × Stroke	78.7 × 77 mm
Valve mechanism	DOHC, 4 valves per cylinder
Maximum power output	77 kw @ 6000 rpm
Maximum torque	135 Nm @ 4800 rpm
Compression ratio	9.8:1
Fuel system	EFI

Table 2 Injector specification

Descriptions	Specification
Voltage range	12–15 Volt
Maximum pressure	16 bar
Controlled	Solenoid

2 Materials and methods

2.1 Vehicle specification

This research was conducted on gasoline cars modified into LPG with the Vapor Phase Injection (VPI) system. Vehicle and injector specifications are presented in Tables 1 and 2, respectively.

With a natural suction system, to achieve a stoichiometric mixture, the amount of injected LPG depends on the air entering the combustion chamber. Therefore, the stoichiometric mixture ($\dot{m}_{stoich}$) on the cylinder is highly dependent on the mass of LPG injected, the number of cylinders (i_{cyl}), and the engine speed (n). The formula to obtain the stoichiometric mixture ($\lambda = 1$) is presented in the following equation.

$$\lambda = \frac{2\dot{m}_{air}}{i_{cyl} \cdot M_{LPG} \cdot m_{LPG} \cdot n} \tag{1}$$

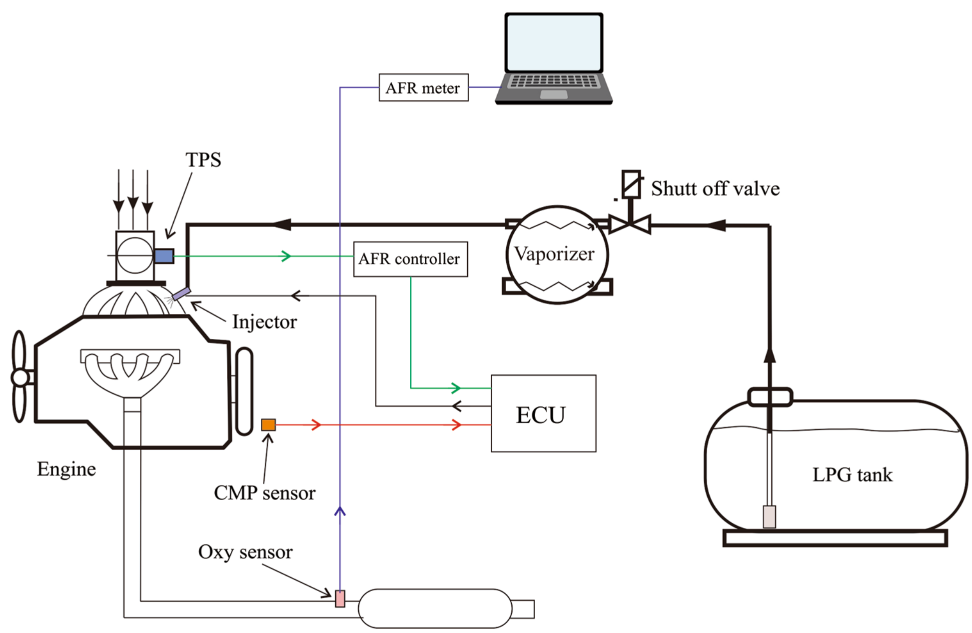
In the VPI system, LPG is divided into two phases, liquid and gas. LPG in the tank until the vaporizer is a liquid phase, while LPG injected into the intake manifold from the vaporizer is a gas phase. The injected LPG depends on the effective flow area—μA (mm^2), injection duration—t_{LPG} (s), gas pressure—ΔP_{LPG} (Pa) at intake manifold temperature—T_0 (K) and pressure—P_0 (Pa). In addition, LPG has c_p of 1750 J/kg K and R_{LPG} of 161.26 J/kmol K, therefore, the mass of the injected LPG is presented in the following equation [36].

$$m_{LPG} = (\mu A)_{LPG} \cdot \frac{p_{0+\Delta P_{LPG}}}{R_{LPG} T_0} \left(\frac{p_0}{p_{0+\Delta P_{LPG}}} \right) \cdot \frac{c_{p-R_{LPG}}}{c_p} \cdot \sqrt{2 \cdot c_p \cdot T_0 \left[1 - \left(\frac{p_0}{p_{0+\Delta P_{LPG}}} \right) \cdot \frac{R_{LPG}}{c_p} \right]} \cdot t_{LPG} \tag{2}$$

2.2 AFR controller

The AFR controller developed in this study worked as a signal manipulator generated by the throttle position sensor (TPS). The controller circuit was paired between the TPS and ECU which was regulating the AFR based on the

Fig. 1 Set up LPG controller and AFR measurement



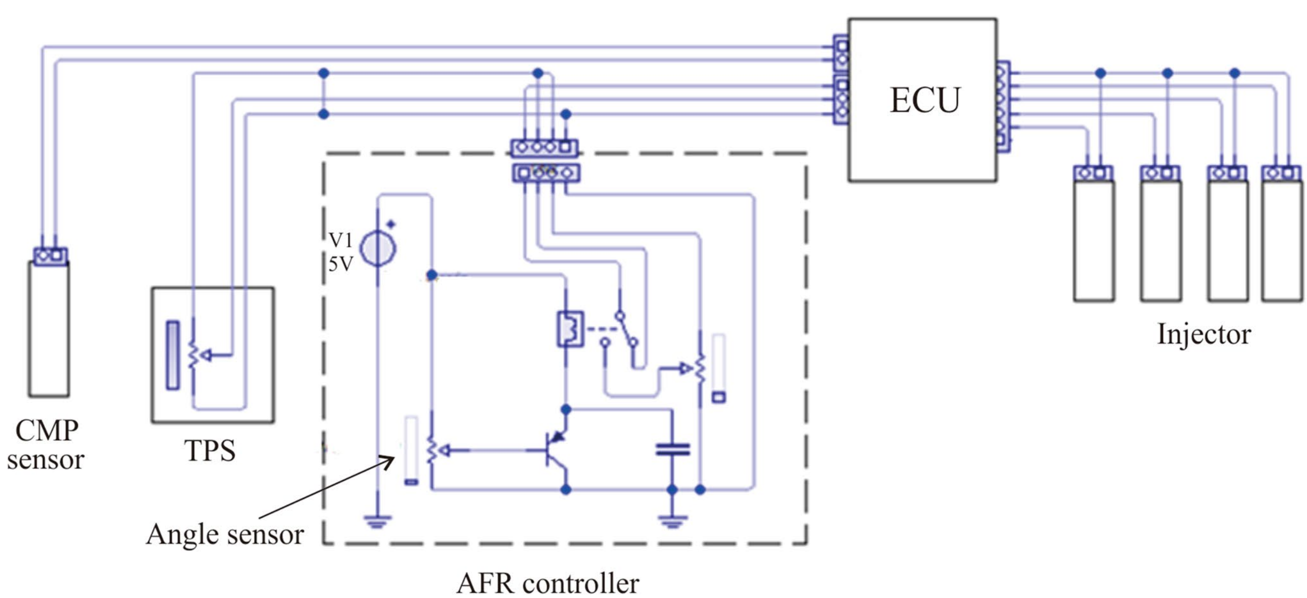


Fig. 2 Wiring diagram of AFR controller

information from the TPS, camshaft position sensor, and signals from other sensors. The injector sprayed LPG in the gas phase to be regulated using the pulse wide modulation (PWM) method. The angle sensor, as a road tilt angle detector, was paired with the AFR controller while the AFR meter obtains data from an oxygen sensor attached to the exhaust manifold. The concept of the LPG controller designed with the AFR data retrieval is presented in Fig. 1.

3 Results and discussion

3.1 Prototyping

The parts of the AFR controller circuit work in an integrated manner, as shown in Fig. 2. For example, the TPS detects the throttle valve position that sends signals to the ECU. Moreover, the controller consists of power supply, angle sensor, transistor, relay, capacitor, and a variable resistor. The power supply, as a voltage source, activates the relay and angle sensor while the NPN transistor activates the relay when it gets triggered from the sensor angle. Furthermore, the capacitor controls the relay just after the trigger from the angle sensor is sent to the transistor and the LPG controller becomes activated by adjusting the sensitivity of the sensor angle. Relay contact points at normally closed terminals are connected to ECU and TPS, while normally open terminals are connected to ECU and variable resistors.

AFR controller works based on the position of the vehicle. When the vehicle is running in the down-way, the angle sensor produces a signal which triggers the

Fig. 3 Installation of oxygen sensors (**a**), clinometer (**b**), LPG injectors (**c**), testing LPG controllers on down-way (**d**)

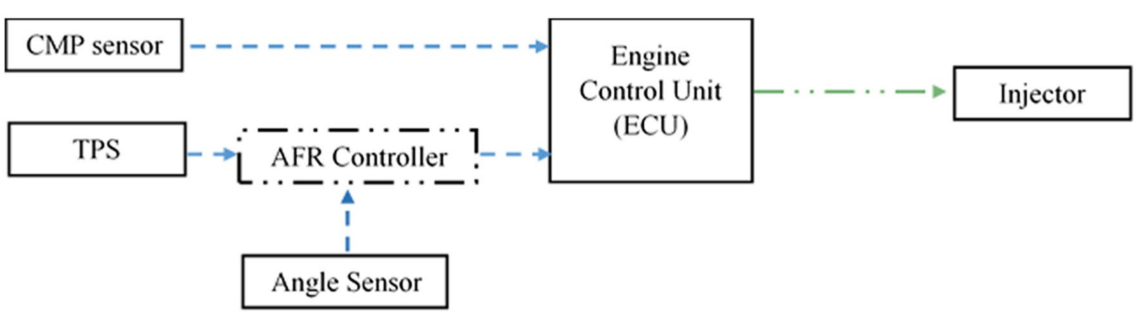


Fig. 4 Block diagram of LPG controller

Table 3 AFR measurement data

Slope angle	Speed gear position	Without AFR controller		With AFR controller	
		AFR	Deviation	AFR	Deviation
10°	1	14.5	±0.4	15.4	±0.3
15°	1	14.6	±0.4	15.6	±0.3
20°	1	14.6	±0.35	15.9	±0.3
10°	2	14.5	±0.2	15.4	±0.3
15°	2	14.6	±0.4	15.6	±0.2
20°	2	14.6	±0.2	15.9	±0.2
10°	3	14.4	±0.3	15.5	±0.3
15°	3	14.6	±0.2	15.6	±0.2
20°	3	14.6	±0.2	15.9	±0.2

transistor to activate the relay. This, however, reduces the voltage from TPS to ECU through a variable resistor. Furthermore, the ECU also reduce the flow of LPG entering the engine through the injectors. Oxygen sensor meters are used to determine the amount of LPG injected as shown in Fig. 3a. Finally, the Clinometer installed to measure the angle of inclination is as shown in Fig. 3b. We use clinometer because it is more practical with high accuracy (maximum deviation is only 0.2° compared to measurements using bevel gauge).

ECU controls LPG injectors based on information from sensors such as CMP for engine speed, TPS for throttle valve opening positions, and an AFR meter attached inside the exhaust manifold to measure mixed quality by monitoring the LPG/air mixture entering the engine. The LPG controller block diagram is presented in Fig. 4.

3.2 AFR measurement

The AFR was measured at varying road slopes including 10°, 15° and 20°. Therefore, the AFR data on speed gear 1, 2 and 3 positions without and with LPG controller at a slope angle of 10°, 15°, and 20° are presented in Table 3. Tests carried out in down-way each of 10 s. For each road-slope, the vehicle is set to start running at 0 s and the AFR controller will work at 2 s and end at 9 s after the vehicle starts. Vehicle speeds are left naturally based on the level of the road slope. The AFR controller is intentionally set at the 2 s after start running to ensure the slope of the vehicle is in the down-way, not at the speed-bump or when the vehicle is stuck in a road pit. Therefore, the AFR value after the 9th second is the same as the initial value, caused by the vehicle being stopped. If the vehicle is travelling in a long down-way, a high AFR will last as long as the vehicle is still detected tilt. The graphs of the test results are presented in Figs. 5, 6, and 7, respectively.

From Table 3 and Figs. 5, 6, and 7, the result shows that the greater slope of the road produced higher AFR. This indicates that the kinetic force and vehicle gravity can be used as input parameters to control the AFR. In previous studies [31, 32], the AFR controller system in LPG vehicles were applied based on decelerations with input parameters from engine, brake, and vehicle speed. In this study, the AFR controller developed has the ability to work on reduced road conditions at low vehicle and engine rotation speeds. Based on the data during observation, this AFR controller has a great potential to be applied to modified LPG vehicles that operate in

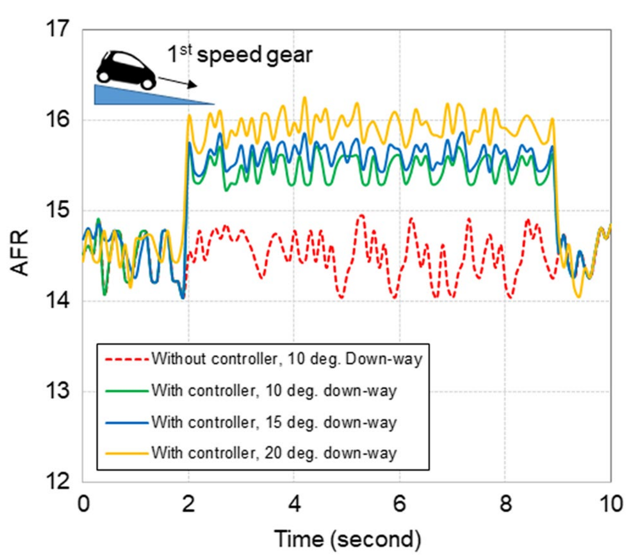


Fig. 5 AFR profile on various road slope at 1st speed gear

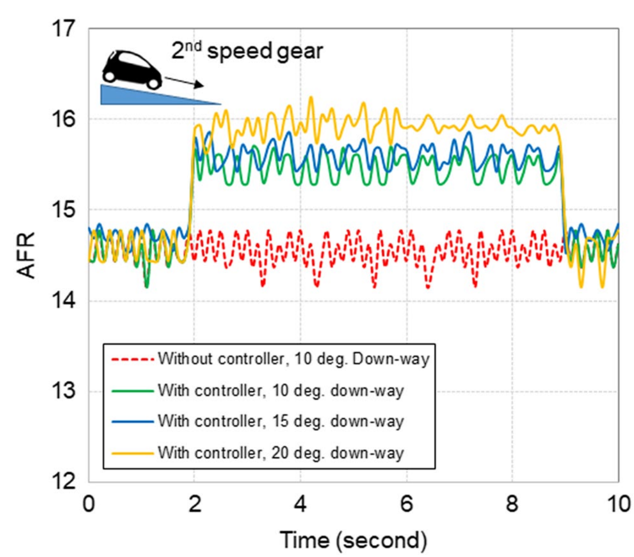


Fig. 6 AFR profile on various road slope at 2nd speed gear

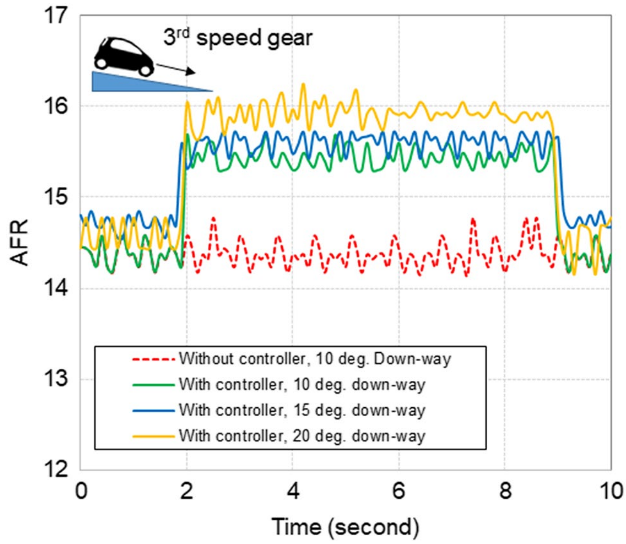


Fig. 7 AFR profile on various road slope at 3rd speed gear

mountainous areas, although this only makes a small contribution to areas with the majority of flat roads.

4 Conclusion

The results showed that the kinetic force, gravity, vehicle weight, and road slope have the potential to be used as input signals by the AFR controller to improve fuel efficiency. The AFR controller developed was able to increase the AFR value from an average value of 14.5 to 15.5–16.2, depending on the down-way angle while the gear position has no measurable effect. Furthermore, a greater slope of the road was observed to have produced greater AFR. In conclusion, the AFR controller has the ability to increase AFR and it is very suitable for modified LPG vehicles with first and second generation of converter kits that are not yet equipped with lambda sensors, especially for LPG vehicles operating in mountainous areas.

Acknowledgements This research is part of an environmentally friendly vehicle development project at the Automotive Laboratory of Universitas Muhammadiyah Magelang. The researchers appreciate the technicians involved in this study.

Compliance with ethical standards

Conflict of interest The author(s) declare that there is no conflict of interest regarding the publication of this article.

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