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Air-Path Control of a Diesel-Dual-Fuel Truck Using Fuzzy Supervisory Controller

Kittipong Yaovaja* and Withit Chatlatanagulchai

Control of Robot and Vibration Laboratory (CRVLAB), Department of Mechanical Engineering, Faculty of Engineering,
Kasetsart University, 50 Ngam Wong Wan Rd, Lat Yao, Chatuchak, Bangkok, 10900
*Corresponding Author: yaovaja@hotmail.com, Telephone Number 089-767-0767, Fax. Number 02-579-4576

Abstract

Diesel-Dual-Fuel Engine is a modified diesel engine by installing a secondary fuel system; which in this case is a natural gas system. In diesel-dual-fuel engines, natural gas as a main fuel is injected in the intake ports of each cylinder of the engine just before intake valve close (IVC). Small amount of diesel is used as pilot fuel which acts like a "liquid" spark plug. The diesel injection strategy is used as main scheme to control the combustion. However, experience shows that these combustion processes are very sensitive to cyclical fluctuations in the thermodynamic state. Thus, sophisticated air-path controller can enhance drivability performance of the engine. PID controller, which is commonly used in engine control, is replaced by Fuzzy Supervisory Controller. Two quantities, mass fresh air flow rate (MAF) and intake manifold absolute pressure (MAP), were controlled in the air-path of the engine. Their set-points varied with wide ranges and with more abrupt changes than those of diesel engine. Variable Nozzle Turbine (VNT) and Exhaust Gas Recirculation (EGR) Valve positions were actuators in the control system. They were supervised based on the engine speed condition to solve the interaction problems between the VNT and the EGR. The 2.5-liters diesel-dual-fuel engine was setup on a Toyota Vigo Champ pick-up truck. It was fully controlled by a Woodward (Mototron) ECU and was programmed by using Matlab and Simulink Real-time Workshop. Experiments were done on real vehicle road tests. The MAF and MAP tracking results showed excellent performance of the proposed control system.

Keywords: Diesel-dual-fuel truck, Fuzzy supervisory control, Air-path control, Engine control.

1. Introduction

In 2010, Thailand imported 56 percentages of the total energy in commercial usage. Thailand also imported 816 barrels of crude oil per day; more than half was used in transportation section.

Thailand has natural gas supply from the Gulf of Thailand, which is a good alternative fuel. Because it is abundant, the price becomes an interesting point to employ natural gas whose price is only one-third of the diesel price.

However, Thailand has successfully exploited only 5 percentages of the produced natural gas, 3,511 million cubic foot of per day, to a natural gas vehicle (NGV). This research focuses on reducing diesel fuel usage in light-duty trucks which is the largest part of energy consumption.

In diesel-dual-fuel (DDF) engine, natural gas or Methane is injected as the main fuel at the intake port and diesel is directly injected into cylinders as a pilot ignition. The small diesel injection ignites the Methane like a "liquid" spark plug, introducing far more energy than the electrical spark plug, which increases the lean burn capability compared to the electrical spark plug case.

Authors did a number of researches on DDF engine control especially on air-path control system since 2009 [1]-[5]. Most of them utilized costly instruments and tested on engine test-bed which is not a practical usage. But in this research, authors did a research on a commercial product and did road tests with a real vehicle.

The OEM ECU of the test vehicle was replaced by a programmable engine control module (ECM) from Woodward. The ECU consists of the ECM as a main processor, an electronic circuit board, and wirings to the vehicle connectors. Matlab & Simulink Real-time Workshop and Woodward’s MotoHawk software are programmed and implemented into the ECU. The tested vehicle and the ECU are shown in Figure 1.

From previous test results on a chassis dynamometer, the DDF engine used 95 percentages less diesel than the original diesel engine. With the high replacement ratio, the engine becomes very sensitive to cyclical fluctuations in the thermodynamic state. The gas injection slightly increases the swing of both MAP and MAF. The MAP and MAF set-points are varied with wide ranges and with more abrupt changes than those of diesel engine. It is crucial that the air-path controller provides accurate tracking control for both quantities simultaneously.

This paper introduces fuzzy supervisory controller to improve the engine performance in the DDF truck. The tested engine has additional actuators in air-path system; variable nozzle turbine (VNT) and swirl valve. VNT vanes are adjusted to achieve fast respond of manifold pressure. Three actuators, considered in this research, are VNT, Exhaust Gas Recirculation (EGR), and throttle.

Figure 1: DDF truck (left), ECU (right)

This paper starts with an introduction section, which is followed by experimental works section. The experimental section shows detail about the DDF truck. Air-path system was observed and discussed in the third section. The fourth section contains the introduction to fuzzy supervisory control and controller design. The fifth section is experimental results and discussion on stationary tests and on road tests. This paper ends with conclusion and reference sections.

2. Experimental Works

This research was done on a real DDF truck. The truck is a 2011 Toyota Vigo Champ shown in Figure 1 (left). The vehicle is two-wheel drive (2WD), double cab, and manual transmission truck.

Toyota 2KD-FTV (VNT) diesel engine was used in this research. The engine has four inline cylinders, 2,494 cubic-centimeter of total engine displacement, 92.0 millimeters in bore, and 93.8

millimeters in stroke. The engine has common-rail direct injection system. The engine performance improves from previous model, 2KD-FTV (I/C), which typically comes from replacing fixed geometry turbo with a VNT. Maximum power increases from 75 kW to 106kW at 3,600 rpm. Maximum torque increases from 260 Nm to 343 Nm during 1,600 to 2,400 rpm. Compression ratio is reduced from previous model, from 18.5:1 to 17.4:1, which reduces engine noise during operation.

Diesel-dual-fuel engine is a modified diesel engine by installing an alternative fuel supply system. In this case, CNG, compressed natural gas, is supplied from Type-I CNG tank which is installed on the pickup truck. Pressure regulator reduces CNG pressure to around 300 kPa before supplies to the engine. Four CNG injectors are located close to non-swirl intake valves.

The engine schematic of the air-path system of Toyota DDF engine is shown in Figure 2. W_{bc} (mass fresh air flow rate before the compressor, (MAF)) is measured by a hot-wire MAF sensor. The intake manifold absolute pressure (MAP) sensor is placed on the intake manifold to measure fluctuation of MAP (p_i). VNT_d is VNT control signal in duty cycle (%). EP_{dc} is duty cycle (%) of EGR control signal, and EP is feedback EGR position (%).

3. Air-Path System Observation

This section's objective is to present ideas about the system characteristic before generating fuzzy supervisory rules.

Various tests were performed when the engine was running at constant engine speed and idle load, and on DDF mode. The truck gear was not engaged, but the engine was controlled to constantly run with idle load at 2,000 rpm. PID controller was applied to control the engine speed by setting the amount of diesel fuel. The power generally came from CNG while a few amount of diesel injection helped engine ignition. Four CNG injectors were constantly commanded at 9 milliseconds duration time.

In order to study the DDF engine, only one actuator was adjusted while the other two actuators were set to constants at each test. The two constant actuators were either set to low or high values, producing four cases of engine

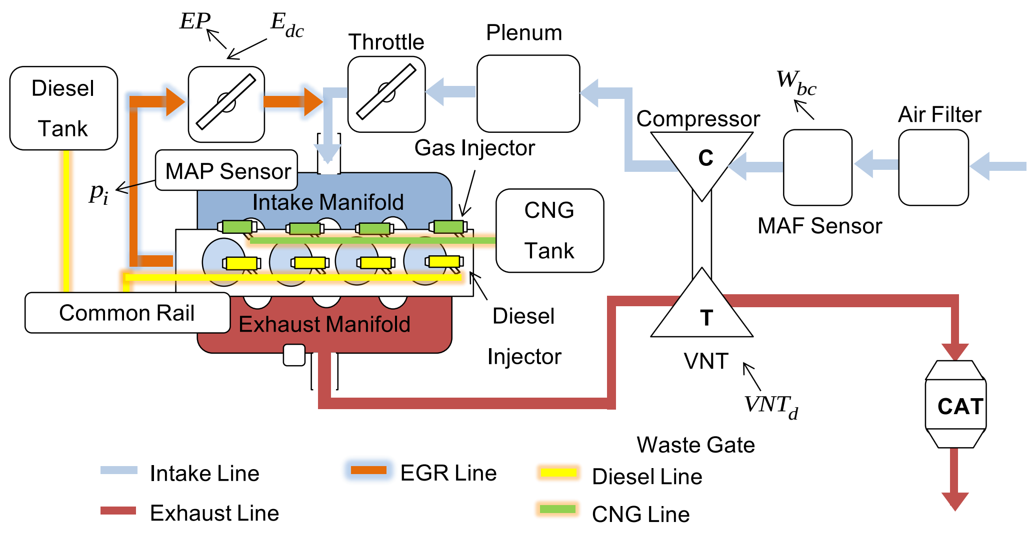

Figure 2: Schematic of air-path system in the DDF engine

conditions. All experimental results of 12 different cases are shown in Figure 3.

VNT was adjusted in A1 - A4 cases, EGR was adjusted in B1-B4 cases, and throttle was adjusted in C1-C4 cases. Their set-points are frequency varying square wave. VNT was constantly set to 24.5 % in B1, B4, C1, and C3 cases, and set to 61% in B2, B4, C2, and C4 cases. EGR was fixed at 0 % in A1, A3, C1, and C2 cases, and fixed at 50% in A2, A4, C3, and C4 cases. Throttle was held at 30 % in A1, A4, B3, and B4 cases, and held at 100% in A1, A2, B1, and B2 cases.

From the experimental results in A1 and A2 cases, VNT position affects the MAP in the same direction, but VNT position affects the MAF in the inverse direction. VNT position could properly control MAP. However, A1 - A4 cases show that when increasing EGR position (from 0 to 50%) VNT command has less effect to MAP. This makes sense to increase VNT control effort with increasing EGR position.

EGR, on the other hand, could be used to control MAF. From B1 and B2 cases, EGR

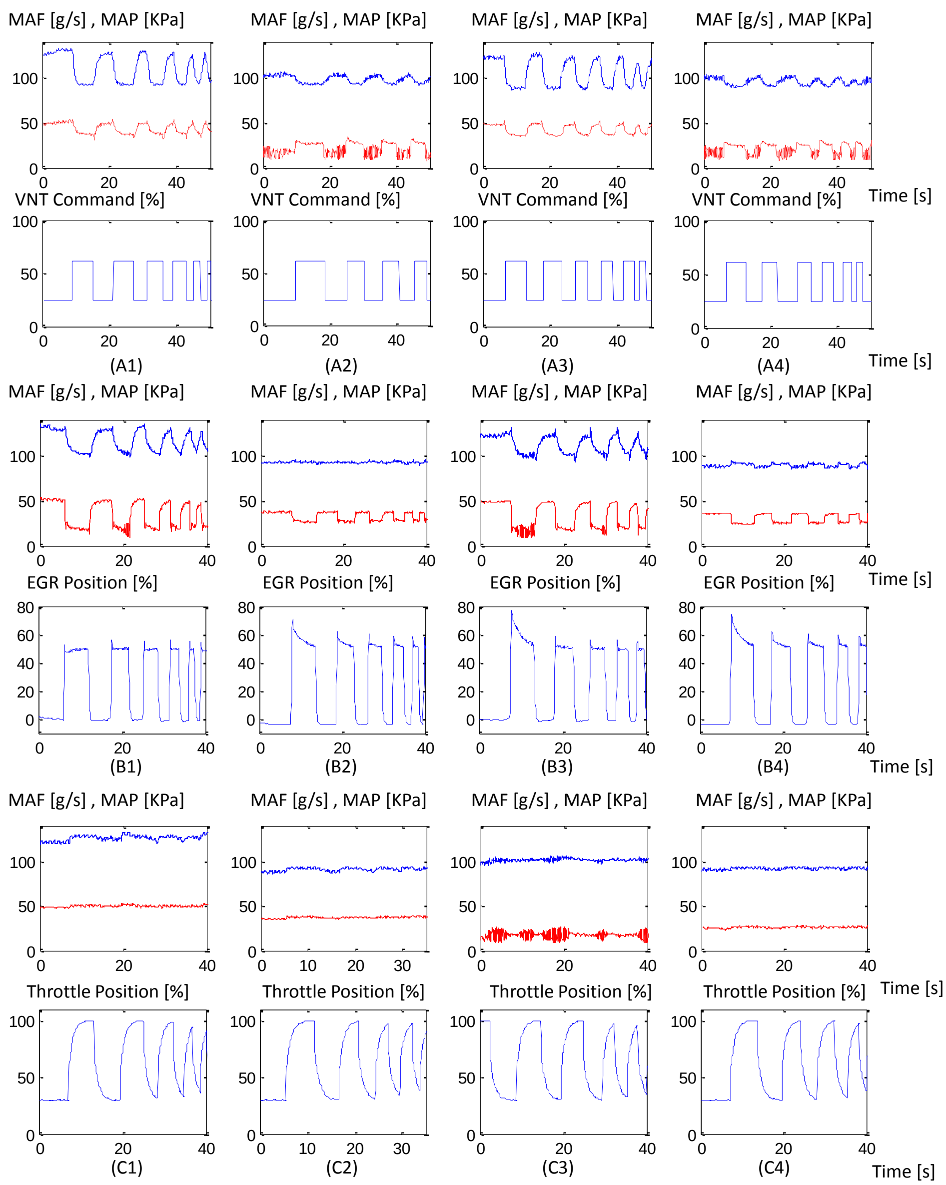

Figure 3: Experimental results from system observation

position affects MAF in the same direction, but EGR position affects MAP only when VNT position is low. B1 - B4 cases show that when increasing VNT position (from 24.5 to 61%), EGR command has less effect to MAF. EGR control effort should be increased with increasing VNT position.

From C1 – C4 cases, throttle command has less effect on both MAF and MAP. In this paper, the throttle position was set to fully open which also increases engine efficiency with no throttling loss.

4. Fuzzy Supervisory Control Design

Fuzzy control is a nonlinear control system which easily allows control designers or experts to put their knowledge into the system. All fuzzy systems in this paper are Takagi-Sugeno fuzzy systems. Fundamental of fuzzy control system can be found in [6]. Air-path fuzzy control can be found in [5], [7]-[9].

The controller schematic is given in Figure 4. The control system consists of two separated fuzzy supervisory control systems.

The fuzzy controller, with MAP tracking error $\left(p_{i,d} - p_i\right)$ or $\left(e_p\right)$ and the integral of e_p as inputs, generates a desired variation of the VNT

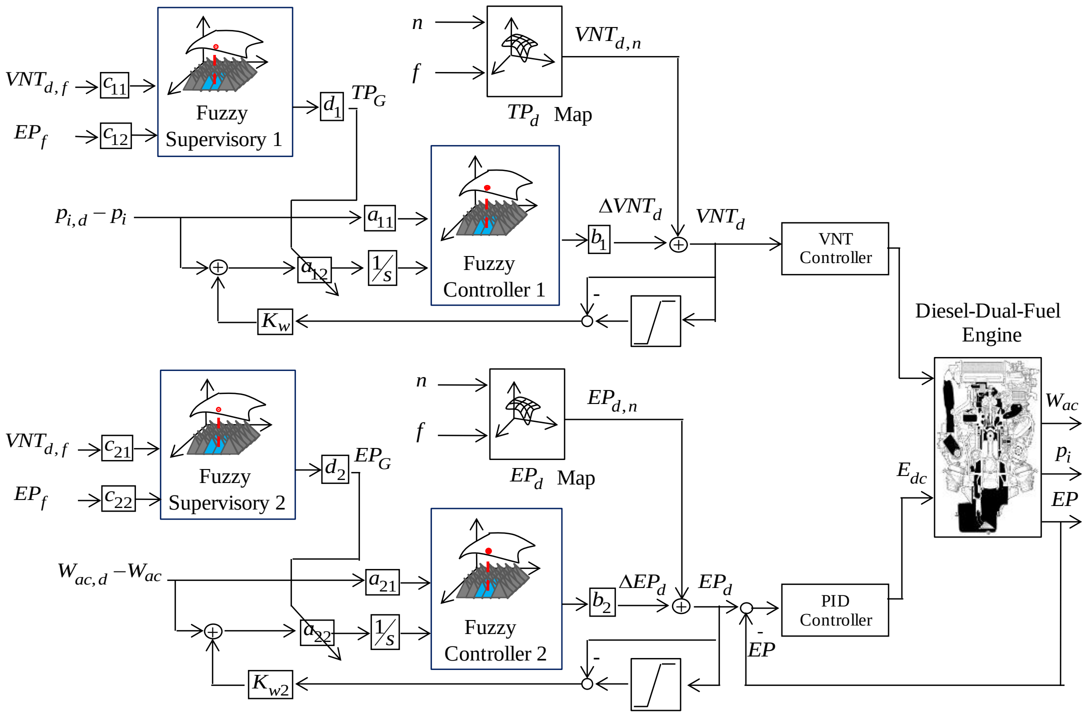

Figure 4: Fuzzy supervisory control system

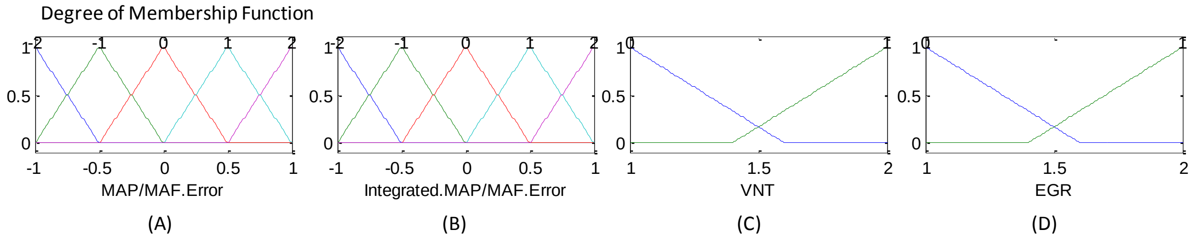

Figure 5: Fuzzy membership functions

command (ΔVNT_d) to minimize the tracking error. The fuzzy supervisor, with the filtered VNT position $(VNT_{d,f})$ and filtered EGR position appropriate VNT variation. The VNT feed-forward map outputs a nominal VNT command $(VNT_{d,n})$ corresponding to engine operation. The variation and the nominal values are added to produce appropriate VNT command. $(EP_{d,f})$ as inputs, generates an appropriate input scaling gain for the fuzzy controller to obtain more.

The EGR fuzzy system is similar to the VNT fuzzy system but with the MAF instead of the MAP. EGR fuzzy system output (EP_d) is sent to PID controller to regulate the EGR position at the set-points.

In this paper, $VNT_{d,n}$ and $EP_{d,n}$ are set to constant values, at 43.5 % and 25%, respectively, in order to entirely demonstrate the fuzzy controller's efforts.

4.1 Fuzzy Controller

The input membership functions are given in Figure 5(A-B). The output membership functions are singleton at (-1, -0.5, 0, 0.5, 1). Input linguistic variables of fuzzy controller 1 are "MAP Error" and "Integrated MAP Error". Input linguistic variables of fuzzy controller 2 are "MAF Error" and "Integrated MAF Error". Output linguistic variables of fuzzy controller 1 and 2 are "Delta VNT" and "Delta EGR", respectively. The fuzzy controller 1 and the fuzzy controller 2 are normalized; all universes of discourse are from -1 to 1. The premise conjunction is "minimum". The defuzzification method is “weighted average”. Control parameters are set as the following: input gains $a_{11} = 0.003$, $a_{12} = 0.008$, $a_{21} = 0.2$, $a_{22} = 0.2$, and output gains $b_1 = b_2 = 100$.

Figure 6(A) contains the rule-bases of the fuzzy systems for the Delta VNT and Delta EGR. The rule-bases in all cases are symmetrical. The input and output linguistic numeric values range from "-2" to "2". The Figure 7(A) shows their corresponding control surfaces; where the outputs of fuzzy controller are plotted against their two inputs. The ΔVNT_d and ΔEP_d are added to produce appropriate VNT command and EGR position set-point.

4.2 Fuzzy Supervisor

The fuzzy supervisor rules generate more proper control effort to solve the interaction problem between VNT and EGR. The fuzzy supervisor improves engine performance from a standard controller.

The filtered VNT position $(VNT_{d,f})$ and the filtered EGR position (EP_f), which are filtered by low-pass filters, are inputs to the fuzzy supervisor

Input linguistic variables of fuzzy supervisory 1 and 2 are "VNT" and "EGR". Output linguistic variables of the fuzzy supervisory 1 and 2 are "VNT Gain" and "EGR Gain", respectively.

Delta VNT		Integrated MAP/MAF Error				
Delta EGR		-2	-1	0	1	2
MAP/MAF Error	-2	2	2	2	1	0
	-1	2	2	1	0	-1
	0	2	1	0	-1	-2
	1	1	0	-1	-2	-2
	2	0	-1	-2	-2	-2

(A)

EGR Gain		EGR	
		0	1
VNT	0	1	0
	1	2	1

(B)

VNT Gain		EGR	
		0	1
VNT	0	1	2
	1	0	1

(C)

Figure 6: Fuzzy rule-bases

The input membership functions are given in Figure 5(C-D). The output membership functions are singleton at (1, 1.5, 2). The premise conjunction is "minimum". The defuzzification method is “weighted average” Control parameters are set as the following; $c_{11} = c_{21} = c_{12} = c_{22} = 0.01$, and $d_1 = d_2 = 1$.

Figure 6(B-C) contain the rule-bases of the fuzzy systems for the VNT Gain and EGR Gain. The input linguistic numeric values range from "0" to "1", while the output linguistic number values range from "0" to "2". Figure 7(B-C) show their corresponding control surfaces; where the outputs of fuzzy controller are plotted against its two inputs. The VNT_G and EP_G are used to adjusted appropriate fuzzy controller input gains.

5. Experimental Results and Discussion

Fuzzy supervisory controller was tested with both stationary tests and road tests before comparing to a well-tuned PID controller.

In stationary tests, MAF and MAP are controlled simultaneously. The results are shown in Figure 8.

In road tests, the DDF truck was driven from first gear to second gear, and to third gear in 30 seconds; engine speeds during the tests are shown in Figure 9(4A-4B). The MAF and the MAP set-points are generated corresponding to engine operations. In Figures 8-9(1A-2B), MAF and MAP set-points are plotted with red dotted lines. Measured MAF and MAP are shown in blue lines.

In Figures 8-9(3A-3B), VNT commands, EGR set-points and EGR positions are plotted with blue line, red dotted line and magenta dashed lines, respectively.

Fuzzy supervisory controller showed precise MAF and MAP tracking control performance during transient operations and in road tests. Fuzzy supervisory gains, in Figure 8(4B), are adjusted in order to handle the interaction problem between the VNT and the EGR.

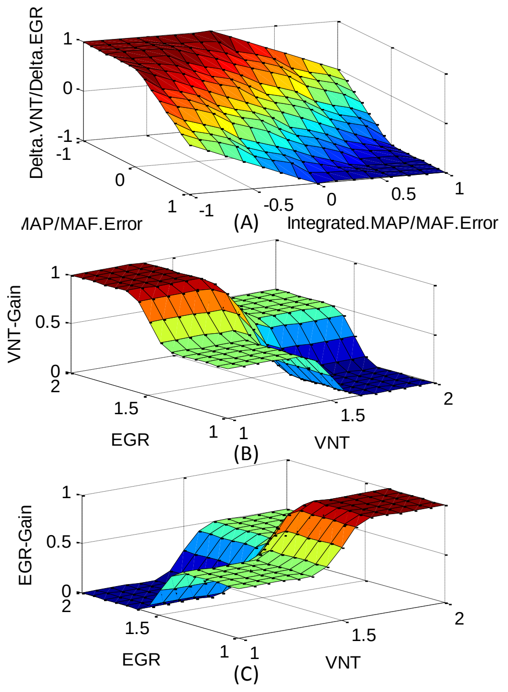

Figure 7: Fuzzy control surfaces

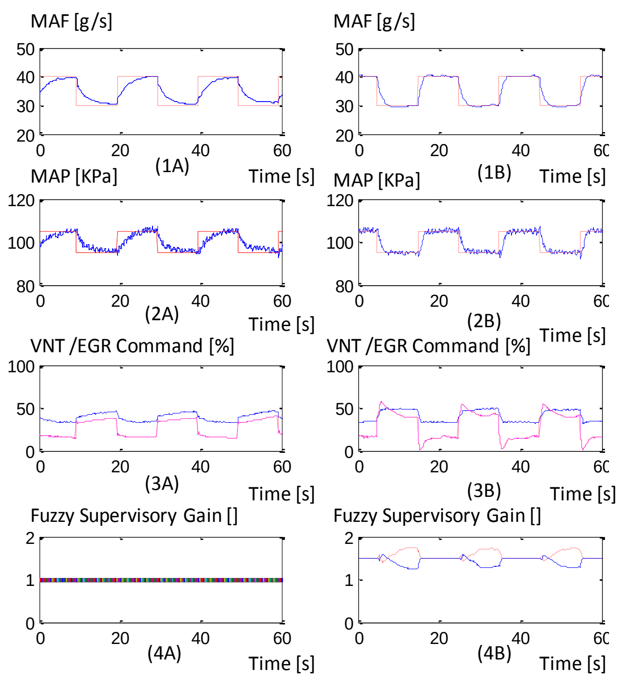

Figure 8: Stationary test results

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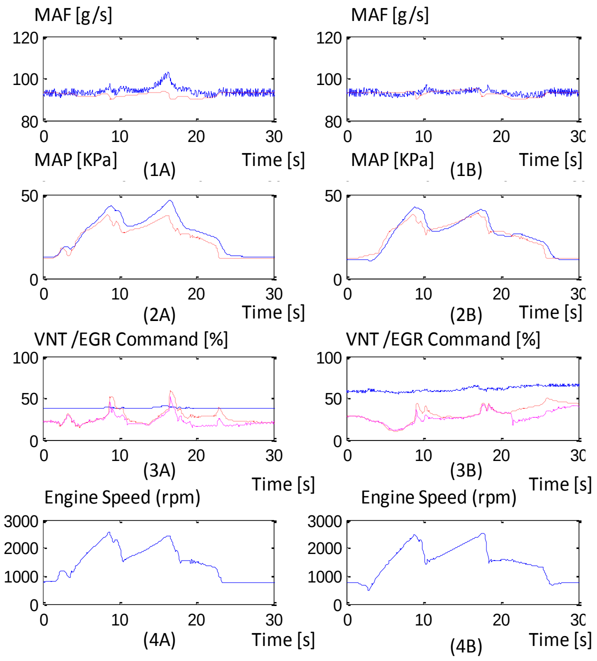

Figure 9: Road test results

6. Conclusion

In the DDF engine, MAP was properly controlled by VNT position, and MAF was suitably controlled by EGR position. However, there is hard interaction between the VNT and the EGR. The fuzzy supervisory controller was successfully implemented on a commercial ECU in the real DDF truck. The experimental results from stationary tests and road tests, the controller can significantly improve the air-path control performance. The interaction of the VNT and the EGR could be further studied; the controller could be more effective, effortless, and uncomplicated

7. Reference

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