

Knock Control in a Diesel-Dual-Fuel Premixed-Charge-Compression-Ignition (DF-PCCI) Engine Using a Fuzzy Supervisory System

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ABSTRACT

Typical diesel-dual-fuel (DDF) engines have compressed natural gas (CNG) injected into the intake ports as the main fuel and diesel injected into the cylinders for ignition. Recently, a new DDF combustion technology, developed and patented by the PTT Public Company Limited, advanced the diesel injection timing to be early in the compression stroke, resulting in higher energy replacement by the CNG and lower emissions than those of typical DDF engines. In the so-called diesel-dual-fuel premixed-charge-compression-ignition (DF-PCCI) engine, the diesel, CNG and air were mixed together during the compression stroke. Auto-ignition could occur at many places in the mixture; therefore, the combustion process was more sudden and violent. The engine experienced heavy knocking at high loads due to the hotter combustion chamber as well as hard combustion during transient stages due to the high in-cylinder pressure gradient. Without knock control, the engine had to be operated conservatively away from the knock threshold and not at its optimum point. This paper presents a novel knock control algorithm using a fuzzy supervisory system. The work progressed with the following steps. First, the knock intensity was measured on-line in a time-domain for each cylinder with one knock sensor per engine. Second, a knock threshold was selected from correlating the knock intensity of the DF-PCCI engine with that of the diesel engine. Third, several factors that affected knock intensity were identified. Fourth, standard fuzzy controllers were used to adjust the set points of those factors to regulate the knock intensity at the knock threshold. Each cylinder was treated separately. Fifth, fuzzy supervisors were used to determine the amount of each factor to be applied at each operating point by adjusting the output gains of the standard fuzzy controllers. Sixth, a DF-PCCI engine, mounted on an engine dynamometer, ran the NEDC test with on-line emissions measurement. Seventh, performance (torque and drivability), efficiency (the amount of CNG that can replace diesel) and emissions (total hydrocarbon emissions, NO_x, CO, and CH₄) were compared with and without knock control. The results showed very good performance with improvements in drivability, efficiency and NO_x emission when the proposed knock control algorithm was applied.

Keywords: diesel-dual-fuel (DDF) engines, auto-ignition, knock control, fuzzy control

INTRODUCTION

PTT Public Company Limited is a natural gas supplier in Thailand, where natural gas is also abundant (PTT Public Company Limited, 2012). For this reason, there is interest in retrofitting existing light-duty trucks to use natural gas. Currently, light-duty trucks use spark ignition (SI) or compression ignition (CI) engines.

SI engines have utilized natural gas successfully due to the similarity between the natural gas and gasoline fuels. With examples including the bi-fuel technology in passenger cars and the dedicated technology in heavy-duty trucks (Kiencke and Nielsen, 2005). However, in CI engines, which have a higher compression ratio, natural gas cannot be used solely because of engine knock, so the diesel-dual-fuel (DDF) technique has been utilized instead (Hou *et al.*, 2010).

In DDF engines, the natural gas is introduced either homogenously by a mixer or port injectors in the air intake or is directly injected in the combustion chamber and the diesel is used as a pilot fuel, which serves as an ignition source (Chatlattanagulchai *et al.*, 2011). Some challenges for DDF development, especially for light-duty pickup trucks, are the poor thermal efficiency and high emission at part load and engine knock at high load. These poor characteristics limit the fraction (energy replacement ratio) of the natural gas that can be used, so only 50% energy replacement can be achieved by the best available DDF technology for passenger cars (Wannatong *et al.*, 2007), based on the standard of New European Driving Cycle (Plotkin, 2009).

The diesel-dual-fuel premixed-charge-compression-ignition (DF-PCCI) concept was developed by PTT Public Company Limited to improve on the DDF concept by aiming to increase the energy replacement to more than 60% with acceptable engine performance and emissions. In DF-PCCI engines, the natural gas is injected at the intake port during the intake stroke; diesel fuel is injected to the combustion chamber early in the

compression stroke. Then, the mixture (natural gas, diesel and air) is compressed. A portion of the mixture of diesel fuel and air might reach the auto-ignition condition first, and then the flame will propagate through the gas and air mixture. Since there are many auto-ignition sources, the combustion process occurs rapidly. A high pressure rise rate and audible noises from this hard combustion as well as from engine knock results (Nwafor, 2002).

This paper focused on light-duty diesel common-rail engines converted to DF-PCCI engines. The DF-PCCI engines experience heavy knocking when applying a high energy ratio at high loads. Otherwise, hard combustion or slight knocking occurs caused by the high in-cylinder pressure gradient during sudden load and speed changes. The knock problem is complex, involving several actuators, and is in need of a sophisticated knock control algorithm.

Existing knock control methods can be separated into event-based and intensity-based methods. In event-based methods, when knock intensity is above a threshold, a knock event is said to occur, and a fixed amount of corrective action is applied. SI engines have violent knocking and are normally suitable for these event-based methods (Woodward Inc., 2008).

In intensity-based methods, the knock intensity is regulated at appropriate set-points. As a result, the engines can be operated near optimal performance without knocking (Stotsky, 2009). In DF-PCCI engines, where the knocking is likely to be less violent than that of the SI engines, the intensity-based methods are more suitable in reducing knocking and hard combustion and improving engine performance and efficiency (Chatlattanagulchai *et al.*, 2011).

Many examples of intensity-based knock control have been reported. Zhu *et al.* (2007) regulated borderline knock for SI engines using closed-loop stochastic limit controls with in-cylinder ionization signals. Giorgetti *et al.* (2006) used hybrid modeling and model predictive control

to control the air path of a gasoline engine to avoid knocking. Yue and Li (2004) applied fuzzy control to regulate knocking in an SI engine. Bolander and Milunas (1996) patented a knock control using fuzzy logic.

Several reports have studied the knock behavior of engines similar to the DF-PCCI engine, including the knock behavior of a one-cylinder engine test bed modified as a DDF engine (Nwafor, 2002; Thayaparan *et al.*, 2007; Wannatong *et al.*, 2007).

The use of a knock sensor or vibration signal to improve the combustion or to control engine knock has been studied, with researchers using a knock sensor signal in the real-time computation of the estimated combustion parameters to control the combustion timing of homogeneous charge compression ignition (HCCI) engines (Bengtsson *et al.*, 2004; Shahbakhti and Koch, 2007; Grondin *et al.*, 2008; Hillion *et al.*, 2008).

In this paper, the design and experimental results of a knock control system applied to a DF-PCCI engine are presented. A 2KD-FTV Toyota diesel engine was modified to perform as a DF-PCCI engine and was installed in a test cell with an engine dynamometer. The NEDC test was programmed into the engine dynamometer.

The knock control system consisted of two fuzzy systems: the fuzzy controller and the fuzzy supervisor. The fuzzy controller receives the knock regulation error and its integral as inputs. A fuzzy rule-base was constructed from human experience on how to control several actuators in order to reduce the knock regulation error. Six parameters were found to affect knocking and were changed by the fuzzy controller. They are: the diesel pilot start of injection (SOI), the diesel main SOI, the energy replacement ratio (the fraction of CNG usage over diesel usage), the total fuel amount, the diesel fuel split between the pilot and main pulses, and the common-rail pressure. By controlling the output gains of the fuzzy controller, the fuzzy supervisor regulates

the amount of change of these six parameters at a specific operating point.

The knock intensity of each cylinder was found from the signal of a knock sensor mounted on the crank case. Windowing, filtering, rectifying, integrating and averaging were used in processing the knock sensor signal. For each cylinder, two windows were used to capture the knock sensor signal at appropriate timings. One window was placed where knocking was most likely to occur, the other window was placed where knocking was less likely to occur and used as a reference. A high-pass filter filtered out low-frequency disturbances especially those from engine rotation. Then, the two signals were rectified and integrated per two engine revolutions before being subtracted and averaged over several engine revolutions and used as an estimate of the knock intensity.

The knock threshold was obtained from running the engine in diesel mode and recording the knock intensity at each operating point. The knock control system then used the difference between the knock threshold and intensity to adjust the fuel amount and timing of each cylinder separately.

By following the NEDC test, with and without the knock control system, the following results were observed.

1. With the knock control system, the DF-PCCI engine achieved a higher overall energy replacement ratio (less diesel, more CNG) because the DF-PCCI engine normally has a higher knock intensity value than its threshold. Therefore, the knock control system adjusted the engine to reduce the knock intensity by increasing the CNG amount used.

2. With the knock control system, the DF-PCCI engine had less audible noise, less vibration, less hard combustion and less knocking than without the knock control system.

3. Similar engine performance in terms of engine output torque was obtained with and without the knock control system.

4. Drivability was also improved with

the knock control system due to less audible noise and less vibration.

5. With the knock control system, NO_x emission was reduced substantially as a result of less hard combustion. However, CH_4 and total hydrocarbon emissions (THC) emissions increased due to more CNG being used and poor adjustment of the SOI at several operating points. CO emission was similar in both cases.

DF-PCCI ENGINE SPECIFICATIONS

Figure 1 depicts a schematic diagram of the DF-PCCI engine. The DF-PCCI engine was modified from a 2KD-FTV Toyota diesel engine, whose specifications are given in Table 1. CNG is injected at the intake ports as in the premixed case. There is one gas injector for every intake port as in multi-point injection. The exhaust gas recirculation (EGR) valve receives exhausted gas from the manifold close to cylinder number 4. There is no intercooler, but one plenum. There is also one mechanical waste gate, which cannot be actuated online. The air path is controlled by actuating the throttle and the EGR valve.

KNOCK INTENSITY FORMULATION

A knock sensor was mounted on the side of the crank case between cylinders number 2 and number 3. The knock sensor senses the acceleration or vibration of the engine. Figure 2 contains a diagram showing how the knock intensity of each cylinder is formulated.

A high-pass second-order Butterworth filter was used with a cut-off frequency of 100 Hz to filter out the low-frequency disturbance signal from engine rotation up to around 3,000 rpm. The sampling period of the control system was 4 ms or 250 Hz. Therefore, the cut-off frequency was less than half of the sampling frequency to obey the Nyquist criterion (Ogata, 2010).

For each cylinder, two crank-angle intervals were selected as windows. One window was from 0 to 30° from top dead center (TDC), where knocking mostly takes place. The other window was from 670 to 700° from TDC (-50 to -20° before TDC), where knocking usually does not occur. This second window was used as a reference window. Since there are four cylinders, in 720° or two engine rotations, there are eight

Table 1 Engine Specifications.

Item	Description
Model	Toyota 2KD-FTV, diesel engine
Number of cylinders	4 (inline)
Number of valves	16 (DOHC)
Manifold	Cross-flow with turbocharger
Fuel system	Common-rail direct injection
Displacement	2,494 cc
Bore	92.0 mm
Stroke	93.8 mm
Connecting rod	158.5 mm
Compression ratio	18.5:1
Maximum power	75 kW at 3,600 rpm
Maximum torque	260 Nm at 1,600–2,400 rpm
Valve timing	
IVO	718 degrees of crank angle
IVC	211 degrees of crank angle
EVO	510 degrees of crank angle
EVC	0 degrees of crank angle
Firing order	1-3-4-2

DHOC = double overhead camshaft; IVO = Intake valve opening; IVC = Intake valve closing; EVO = Exhaust valve opening; EVC = Exhaust valve closing.

windows. Each window captured the knock sensor signal at different time.

The current crank-angle position with respect to the TDC of each cylinder was computed according to Equation 1:

$$\text{Current local CA position} = \frac{\text{Remainder}}{720} \left[720 - \left(\begin{array}{l} \text{Global TDC offset} \\ + \text{Local TDC offset} \end{array} \right) \right] + \text{Current global CA position} \quad (1)$$

where CA = Crank angle, TDC = Top dead center and the global TDC offset for the engine is 88 crank-angle degrees, the local TDC offset for cylinder 1 is 0°, for cylinder 2 is 540°, for cylinder 3 is 180° and for cylinder 4 is 360° and

the current global CA position is measured from the global TDC.

Both the knock and non-knock signals from both windows were then rectified before being integrated and peak held. Their peak values were subtracted before sending to the window-moving average over a four-second interval, which equals 100 two engine rotations running at 3,000 rpm. The output signal became the knock intensity, with each cylinder having its own knock intensity. It was observed that the knock intensity correlated very well with the audible engine noise from hard combustion (high pressure gradient).

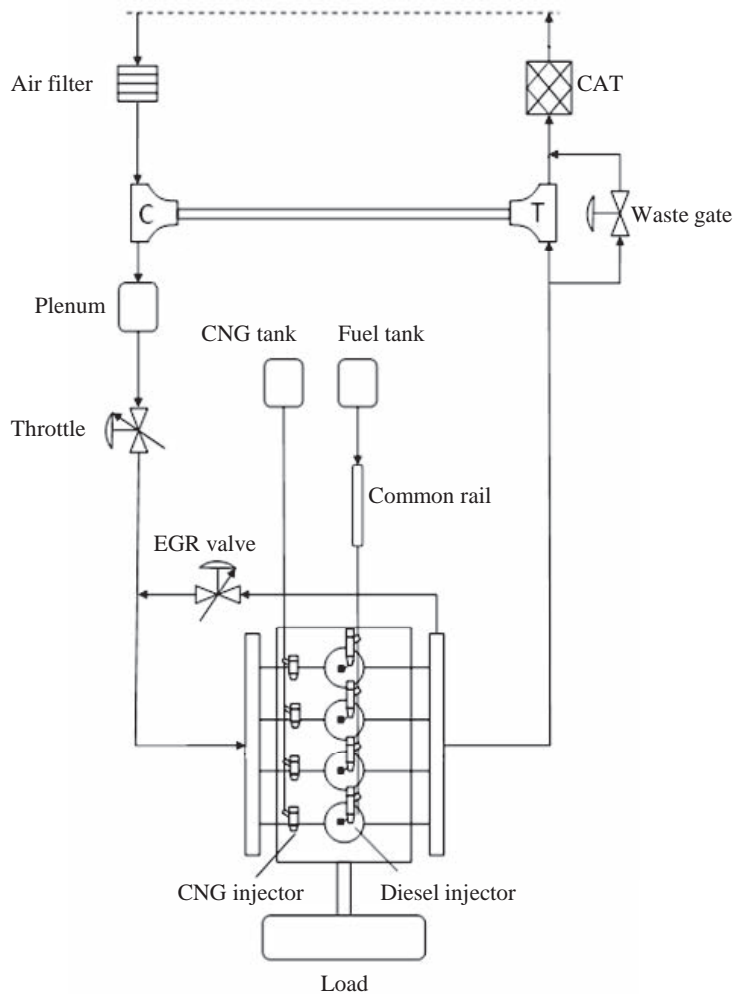


Figure 1 Overall schematic diagram of the diesel-dual-fuel premixed-charge-compression-ignition engine. (CAT = catalytic converter, C = Compressor, T = Turbine, CNG = Compressed natural gas, EGR = Exhaust gas recirculation.)

DF-PCCI INJECTION STRATEGY

To understand the functions of the knock control system, it is necessary to understand first the injection strategy of the DF-PCCI engine which is shown in Figure 3.

The engine speed, engine coolant temperature and DF-PCCI on/off switch are inputs

to the state machine that determines the current state of the engine. There are four states: stall, crank, run diesel and run DF-PCCI. In the stall state, no fuel is injected. During the crank state, only diesel fuel is injected as pre injection. Three diesel injection pulses are possible, which are called pre, pilot and main in order according to their injection timing.

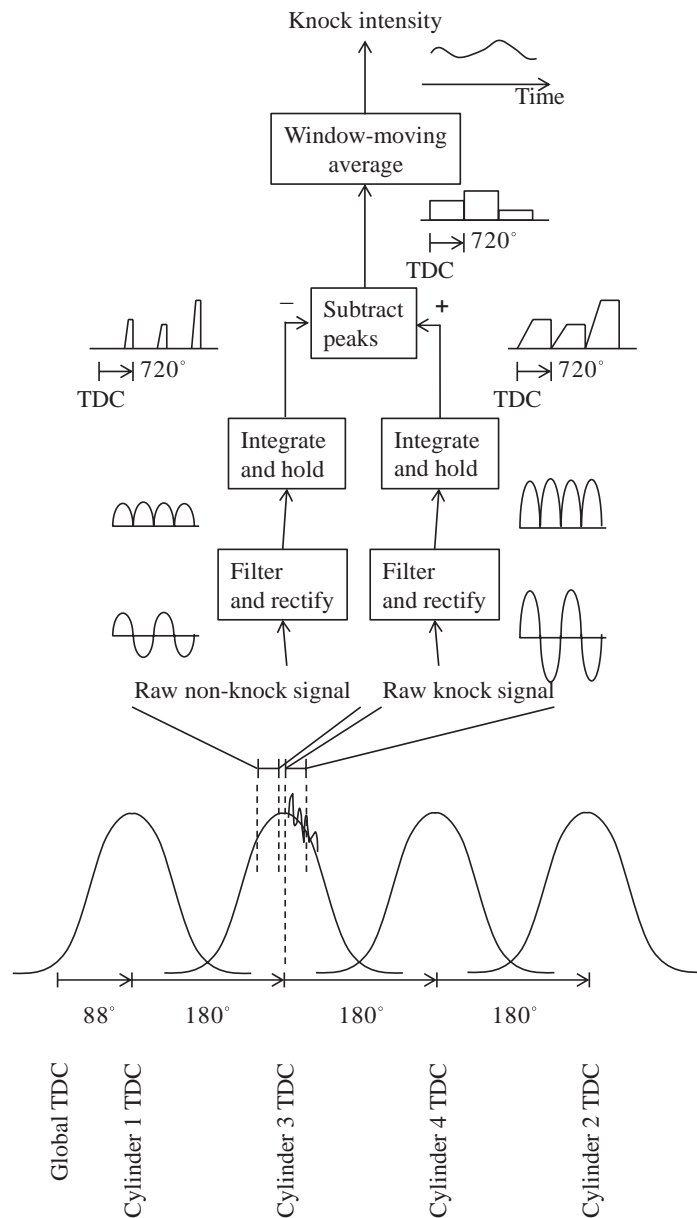


Figure 2 Diagram showing knock intensity formulation. (TDC = Top dead center)

The injection strategy is divided into eight zones with respect to the operating point, which is determined by 1) the engine speed and 2) the engine load or indicated mean effective pressure (IMEP). Figure 4 shows the zone number as a function of the engine speed and IMEP. There is a fixed map to determine the zone number.

Zone 0 is idle; where there is either one main injection or two (pilot and main) injections

depending on the engine speed and IMEP. There is no CNG injected during idle.

Zone 1 and zone 2 have both diesel pilot and main injections and CNG injection. The CNG injection timing always ends at 270° before TDC to avoid CNG being left behind, whereas the CNG injection duration can be adjusted. In zone 1 and zone 2, cylinders number 2 and 3 are skipped (no fuel injections are given) to obtain a sufficiently

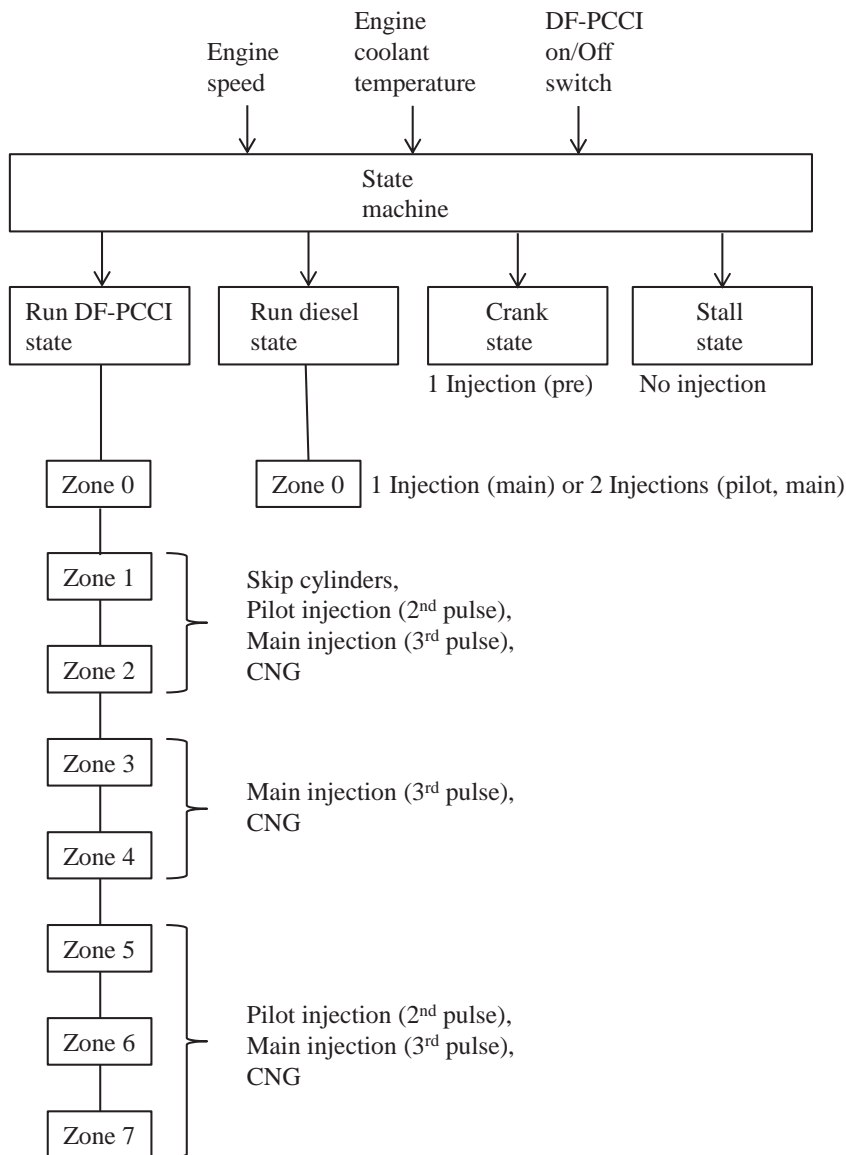


Figure 3 Block diagram showing the injection strategy of the diesel-dual-fuel premixed-charge-compression-ignition (DF-PCCI) engine. (CNG = Compressed natural gas.)

strong combustion per cylinder. The difference between zone 1 and 2 is the energy replacement ratio, where zone 2 uses more CNG than zone 1.

Zone 3 and zone 4 have only diesel main injection and CNG injection without skipping cylinders. The missing of the pilot injection provides smooth combustion during zone changes because all four cylinders now combust. The difference between zones 3 and 4 is the energy replacement ratio, where zone 4 uses more CNG than zone 3.

Zones 5, 6 and 7 have both diesel pilot and main injections and CNG injection without skipping cylinders. The higher the zone number, the higher the energy replacement ratio used.

Several terms involved with the injection duration are:

1. Energy replacement ratio: the fraction of the energy represented by CNG divided by the total fuel energy

2. Fuel split: the fraction of the diesel pilot injection duration divided by the diesel main injection duration

3. Total fuel: the fraction determining the total amount of fuel used.

The diesel pilot and main injection durations and CNG injection duration can be

computed from the terms above according to Equations 2–4:

$$\text{Diesel pilot duration} = \text{Total fuel} \times (1 - \text{Replacement ratio}) \times \text{Fuel split} \quad (2)$$

$$\text{Diesel main duration} = \text{Total fuel} \times (1 - \text{Replacement ratio}) \times (1 - \text{Fuel split}) \quad (3)$$

$$\text{CNG duration} = \text{Total fuel} \times \text{Replacement ratio} \quad (4)$$

where all durations are measure in milliseconds.

CONTROL SYSTEM DESIGN

The DF-PCCI engine experienced the following knocking and knock-related incidents.

1. Heavy knocking occurred when using a high energy replacement ratio at high loads because at high load, the air/methane mixture is exposed to hotter temperatures. As such, the auto-ignition of the air-methane mixture is easier to achieve. A greater amount of early diesel injection overly promoted rapid energy release rates during combustion. Decreasing the fuel split and/or decreasing the rail pressure helped to reduce the rapid combustion rate.

2. Hard combustion (as characterized by a high in-cylinder pressure gradient) created noise, especially during the transient stage. This

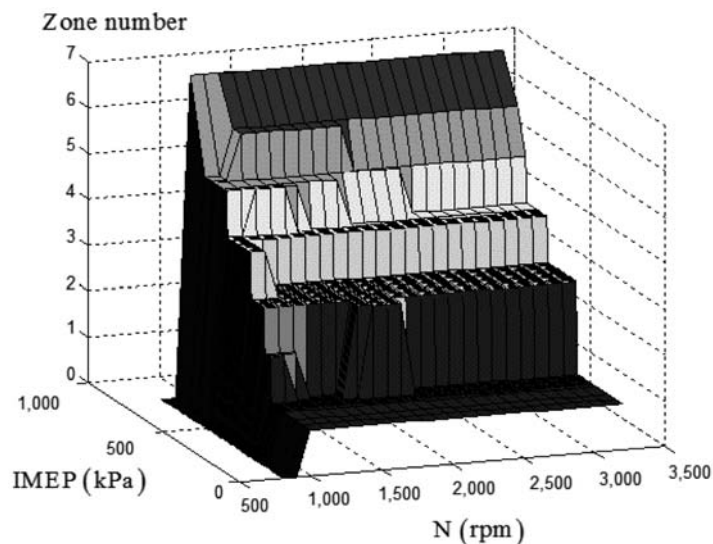


Figure 4 Zone number as a function of engine speed (N) and engine load (IMEP).

incident was less severe than engine knocking. However, it created a high level of audible noise, which required reduction. There were two kinds of hard combustion found.

2.1 Hard combustion or slight knocking occurred during a sudden load decrease. At low load, the diesel injection timing was forced to retard while the combustion chamber temperature was still high as a result of the high load operation of the previous cycles. Compared to steady-state low-load operations, the combustion chamber surfaces are hotter which then heats up the mixture temperature. This condition favored the onset of auto-ignition and a more rapid combustion rate.

2.2 Hard combustion or slight knocking occurred during a sudden load increase (heavy acceleration). During heavy acceleration, diesel replacement was decreased, which required more diesel to be used.

From the test-cell experiments, six parameters were identified that affected knocking. They are listed in Table 2 along with their suggested tuning directions to reduce knocking.

Figure 5 depicts the proposed knock control system. There are three main parts: the threshold map, fuzzy controller and fuzzy supervisor, which are explained below.

Threshold map

The appropriate knock threshold values were determined experimentally as a function of engine speed (N) and engine load (IMEP) by observing the knock intensity of the diesel engine running at various operating points. Each cylinder

has a threshold gain f_i , $i = 1, 2, 3, 4$ to adjust the value from the threshold map further. Due to the positioning of the knock sensor between cylinders number 2 and 3, their gains are set to 1, whereas the gains of cylinders number 1 and 4 are set to 0.8. $n_{d,i}$, $i = 1, 2, 3, 4$, represents desired the knock intensity of each cylinder.

Fuzzy controller

The knock intensity of the i^{th} cylinder is computed on-line and is fed back to find the regulating error $e_i(t)$ and its integral $\int e_i dt$, which are two inputs to the fuzzy controller. The input gains g_{11} and g_{12} are two scaling gains, which convert the inputs to a number within the range -1 to 1. Then, g_{11} is set to 0.005, whereas g_{12} is set to 1×10^{-7} . An integral wind-up algorithm is used to prevent the integral value from going unbounded.

The fuzzy controller is normalized, that is, all universes of discourse are from -1 to 1. There are six input membership functions with linguistic numeric values of -3, -2, -1, 1, 2, 3, respectively. All input membership functions have a symmetrical triangular shape and are fully overlapped. There are 11 output membership functions with linguistic numeric values of -5, -4, -3, -2, -1, 0, 1, 2, 3, 4 and 5, respectively. All output membership functions have a symmetrical triangular shape and are fully overlapped. The premise conjunction is "minimum". The defuzzification method is center of gravity (COG).

The output gain h_{11} belongs to the Δ pilot SOI set-point. The output gain h_{12} belongs

Table 2 Parameters affecting knocking.

Parameter	To reduce knocking/hard combustion
Diesel pilot SOI timing	Retard
Diesel main SOI timing	Advance
Energy replacement ratio	Increase (use more CNG)
Total fuel	Decrease (use less diesel and CNG fuel)
Fuel split	Decrease (use less pilot injection duration)
Rail pressure	Decrease to reduce injection pressure (reduce atomization)

SOI = Start of injection; CNG = Compressed natural gas.

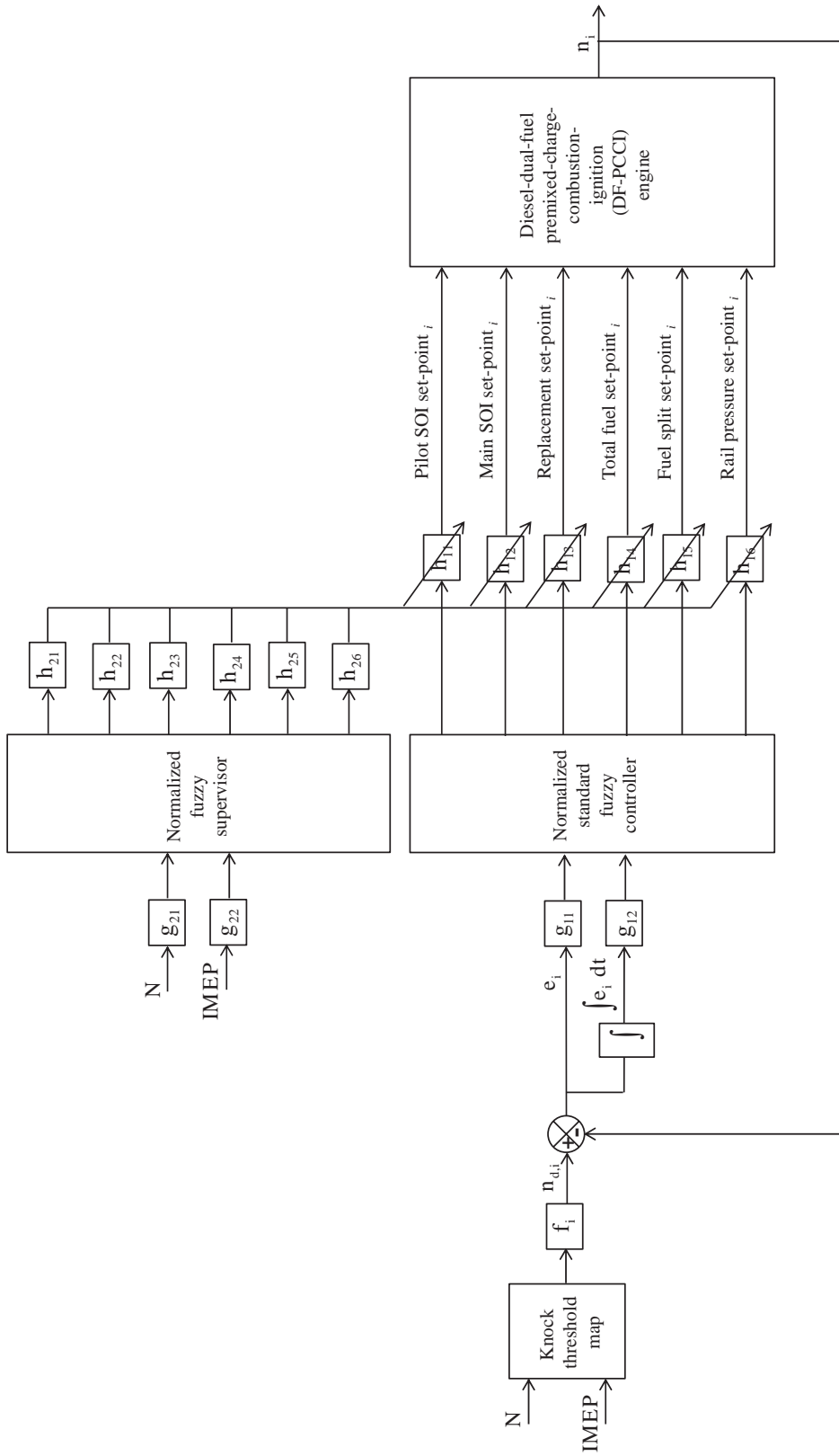


Figure 5 Proposed knock control system, where f represents threshold gain, g represents input gain and h represents output gain and the subscript numbers represent different cylinders. (N = Engine speed, IMEP = Engine load, SOI = Start of injection.)

to the Δ main SOI set-point. The output gain h_{13} belongs to the Δ replacement set-point. The output gain h_{14} belongs to the Δ total fuel set-point. The output gain h_{15} belongs to the Δ fuel split set-point. The output gain h_{16} belongs to the Δ common-rail pressure set-point. All Δ values are added to the nominal set-points from their corresponding maps, which were obtained during steady-state calibrations. All output gains are adapted based on the outputs of the fuzzy supervisor.

Table 3 contains the rule-base of the fuzzy systems for the Δ pilot SOI set-point, the Δ total fuel set-point, the Δ fuel split set-point and the Δ rail pressure set-point. Table 4 contains the rule-base of the fuzzy systems for the Δ main SOI set-point and the Δ replacement set-point.

Fuzzy supervisor

The engine speed and IMEP enter the fuzzy supervisor with input scaling gains g_{11} and g_{22} , which scale the inputs to within the range 0 to 1. To cover the engine speed up to 4,000 rpm, the gain g_{21} is set to 0.00025. To cover IMEP up to 1,000 kPa, the gain g_{22} is set to 0.001.

The fuzzy system is normalized such that all universes of discourse are from 0 to 1. There are six input membership functions with linguistic numeric values of -3, -2, -1, 1, 2 and 3, respectively. All input membership functions have a symmetrical triangular shape and are fully overlapped. There are 11 output membership functions with linguistic numeric values of -5, -4, -3, -2, -1, 0, 1, 2, 3, 4 and 5, respectively. All

Table 3 Rule-base of the standard fuzzy system for the Δ pilot start of injection set-point, the Δ total fuel set-point, the Δ fuel split set-point and the Δ rail pressure set-point.

	$\int e_i dt \times g_{12}$					
	-3	-2	-1	1	2	3
$e_i \times g_{11}$						
-3	-5	-4	-3	-2	-1	0
-2	-4	-3	-2	-1	0	1
-1	-3	-2	-1	0	1	2
1	-2	-1	0	1	2	3
2	-1	0	1	2	3	4
3	0	1	2	3	4	5

e_i = Regulating error for cylinder i ; g = Input gains.

Table 4 Rule-base of the standard fuzzy system for the Δ main start of injection set-point and the Δ replacement set-point.

	$\int e_i dt \times g_{12}$					
	-3	-2	-1	1	2	3
$e_i \times g_{11}$						
-3	5	4	3	2	1	0
-2	4	3	2	1	0	-1
-1	3	2	1	0	-1	-2
1	2	1	0	-1	-2	-3
2	1	0	-1	-2	-3	-4
3	0	-1	-2	-3	-4	-5

e_i = Regulating error for cylinder i ; g = Input gains.

output membership functions have a symmetrical triangular shape and are fully overlapped. The premise conjunction is "minimum". The defuzzification method is center of gravity (COG).

The parameters of h_{21} , h_{22} , h_{213} , h_{24} , h_{25} , and h_{26} are fuzzy supervisor output gains belonging to Δ pilot SOI set-point, Δ main SOI set-point, Δ replacement set-point, Δ total fuel set-point, Δ fuel split set-point and Δ common-rail pressure set-point, respectively. The output gains h_{21} to h_{26} adjust the outputs which are the values of the gains h_{11} to h_{16} , respectively. Note that the h_{21} to h_{26} gains can be viewed as upper bounds of the gains h_{11} to h_{16} . The gain h_{21} is set to 10. The gain h_{22} is set to 10. The gain h_{23} is set to 0.2. The gain h_{24} is set to 3. The gain h_{25} is set to 0.1. The gain h_{26} is set to 10.

Figure 6 contains the control surfaces representing the rule-bases of the fuzzy supervisors for the gains h_{21} to h_{26} , respectively.

From Figure 6a and 6b, the option was selected to adjust the pilot SOI set-point gain and the main SOI set-point gain more toward increasing the load because a larger amount of diesel is used during high load, tolerating a greater timing adjustment. From Figure 6c, it can be seen that the Δ replacement set-point gain is reduced during high load based on practical experience in the study that too much CNG can cause an SI-like knocking from the hot combustion chamber. From Figure 6d and Figure 6e, it can be seen that during high load it is necessary to decrease the adjustment of the first pulse amount since this can affect engine performance. From Figure 6f, it is possible to increase the adjustment of the rail pressure with increasing load due to the larger amount of diesel used at high load.

EXPERIMENTAL RESULTS

The proposed knock control system was implemented with a DF-PCCI engine connected with an engine dynamometer programmed to

run according to the NEDC test. The NEDC is supposed to represent the typical usage of a car in Europe. It consists of four repeated ECE-15 urban driving cycles (UDC) and an ECE R101 extra-urban driving cycle (EUDC). The experimental results with and without knock control were analyzed.

Figure 7 shows the knock intensity results with and without knock control, together with the knock threshold. It can be seen that the knock intensity with knock control is substantially less than that of without knock control, especially at peak values.

Figure 8a–8f show the Δ pilot SOI set-point, Δ main SOI set-point, Δ replacement set-point, Δ total fuel set-point, Δ fuel split set-point and Δ common-rail pressure set-point, respectively.

Figure 9a–9d show the diesel pilot duration, the diesel main duration, the CNG duration and the zone number, respectively.

Figure 10a–10e show the amount of NO_x , CH_4 , total hydrocarbon, CO_{high} and CO_{low} , respectively.

DISCUSSION

The knock intensity correlated well with the level of audible noise from the hard combustion. Smoother engine operation was experienced in terms of noise and vibration with the proposed knock control. It was noted that the minimum values with knock control were higher than those without knock control because with knock control, the knock intensity tried to follow the knock threshold, which can be selected to obtain the optimum combustion strength for all operating points, including the low load/low speed points.

From the results of the Δ pilot SOI set-point, Δ main SOI set-point, Δ replacement set-point, Δ total fuel set-point, Δ fuel split set-point and Δ common-rail pressure set-point, all Δ set-points behaved as expected in order to regulate

the knock intensity at its threshold. The limits of each Δ set-point followed its output gain of the fuzzy supervisor.

As expected, the case with knock control used less diesel pilot and main durations as a result of the lower total fuel set-point. The diesel main duration increased more than the diesel

pilot duration as a result of the lower fuel split set-point. CNG usage also increased with knock control due to the higher energy replacement ratio set-point. On average, throughout the operation of the NEDC test, the amount of diesel used was reduced by 6%, whereas the amount of CNG used increased by 7%. The higher amount of changes

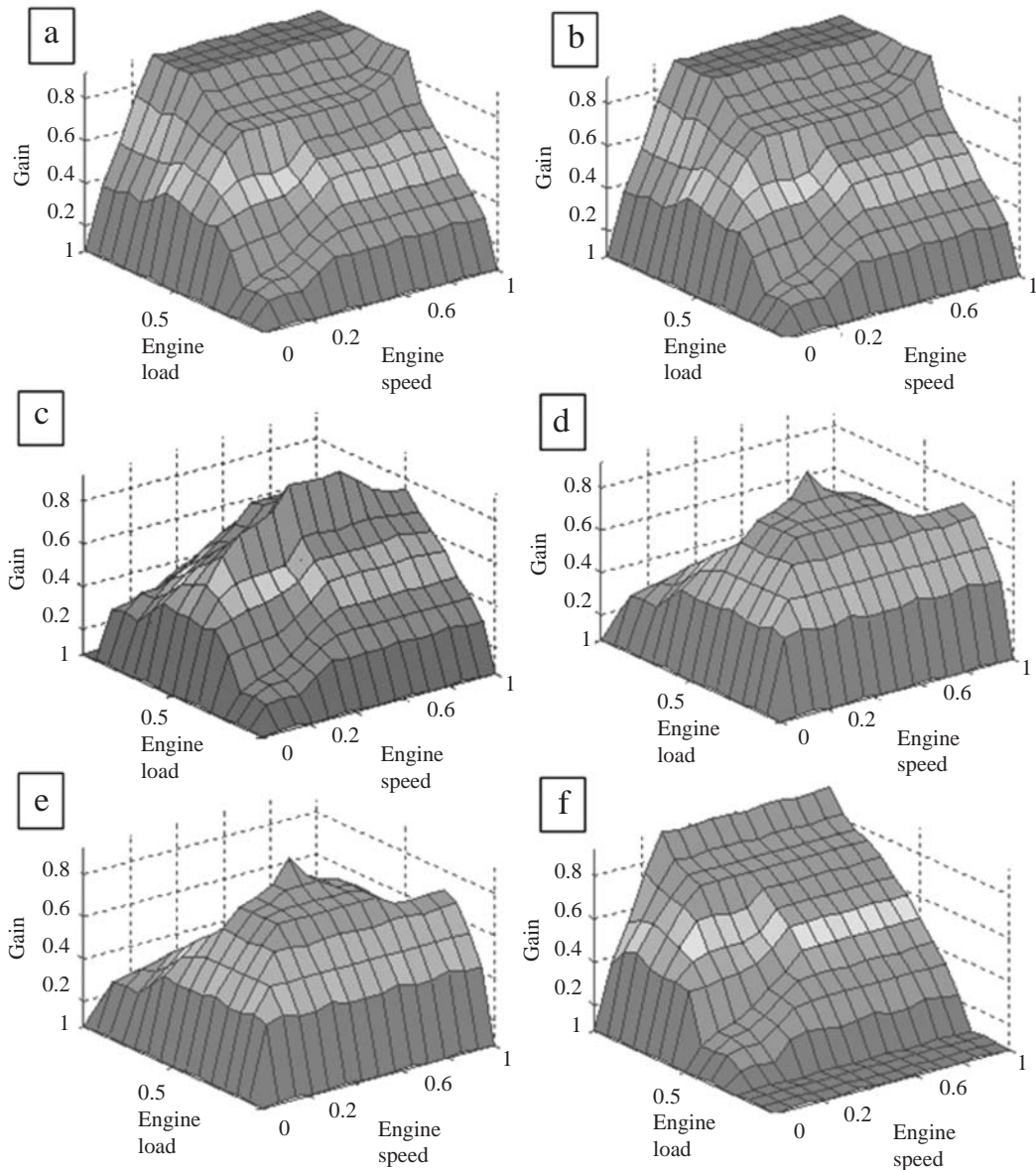


Figure 6 Control surfaces representing the rule-bases of the fuzzy supervisors for: (a) Δ Pilot start of injection (SOI) set-point; (b) Δ Main SOI set-point; (c) Δ Replacement set-point; (d) Δ Total fuel set-point; (e) Δ Fuel split set-point; (f) Δ Common-rail pressure set-point.

in fuel used was more obvious for zones number 3 to 7 where more fuel was injected for a higher load. However, there was a tradeoff between fuel efficiency and engine performance and emissions, which must be taken into consideration, especially in selecting the appropriate knock threshold.

With knock control, the level of NO_x was reduced substantially due to reduced hard combustion. With knock control, the levels of CH_4 and THC increased as a result of more CNG use, a shift in SOI timings and the lower common-rail pressure. However, the level of CO was similar with knock control to without knock control.

CONCLUSION

A knock control system was developed for a DF-PCCI engine. The control system consisted of a fuzzy controller and a fuzzy supervisor. The fuzzy controller reduced the regulation error between the knock intensity and its threshold,

whereas the fuzzy supervisor adjusted the amount of various pertinent set-points to be suitable for each operating point.

From the NEDC test, with the knock control, substantially less engine vibration and audible noise were observed together with a reduction in diesel usage and an increase in CNG usage. With the knock control, the DF-PCCI engine emitted less NO_x , but more CH_4 and THC, which had to be handled by the catalytic converter system.

The engine vibration, as recorded by the knock sensor as the knock intensity signal, correlated well with the combustion quality. Since the knock sensor is available in most commercial pick-up trucks, future efforts should be toward using the knock intensity signal to adjust the set-point values coming out of fixed maps, which are normally obtained during steady-state engine calibrations, for better combustion quality.

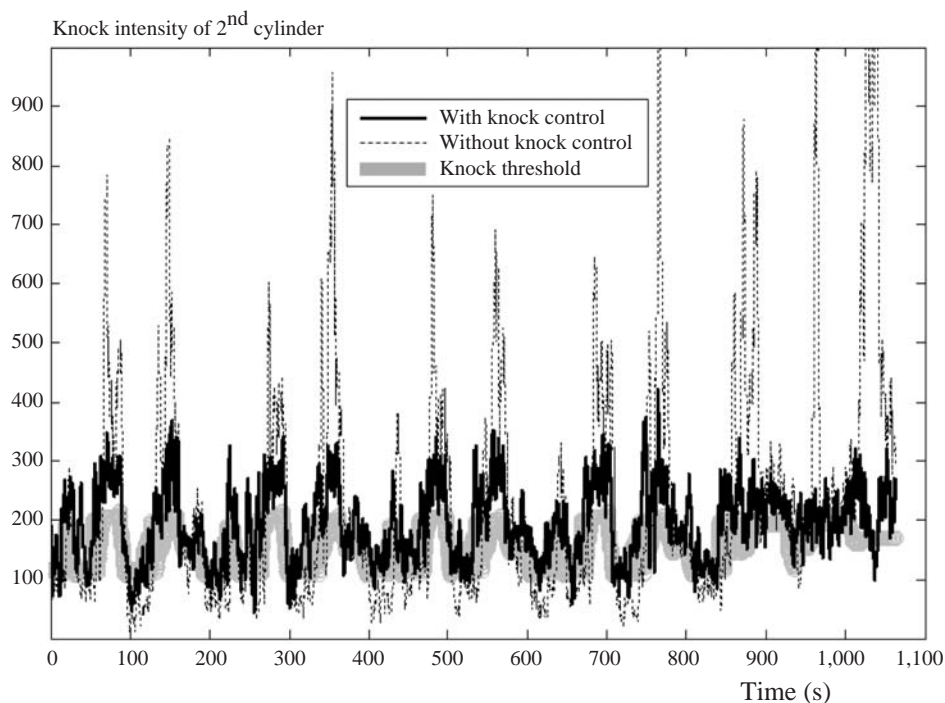


Figure 7 Knock intensity of cylinder 2.

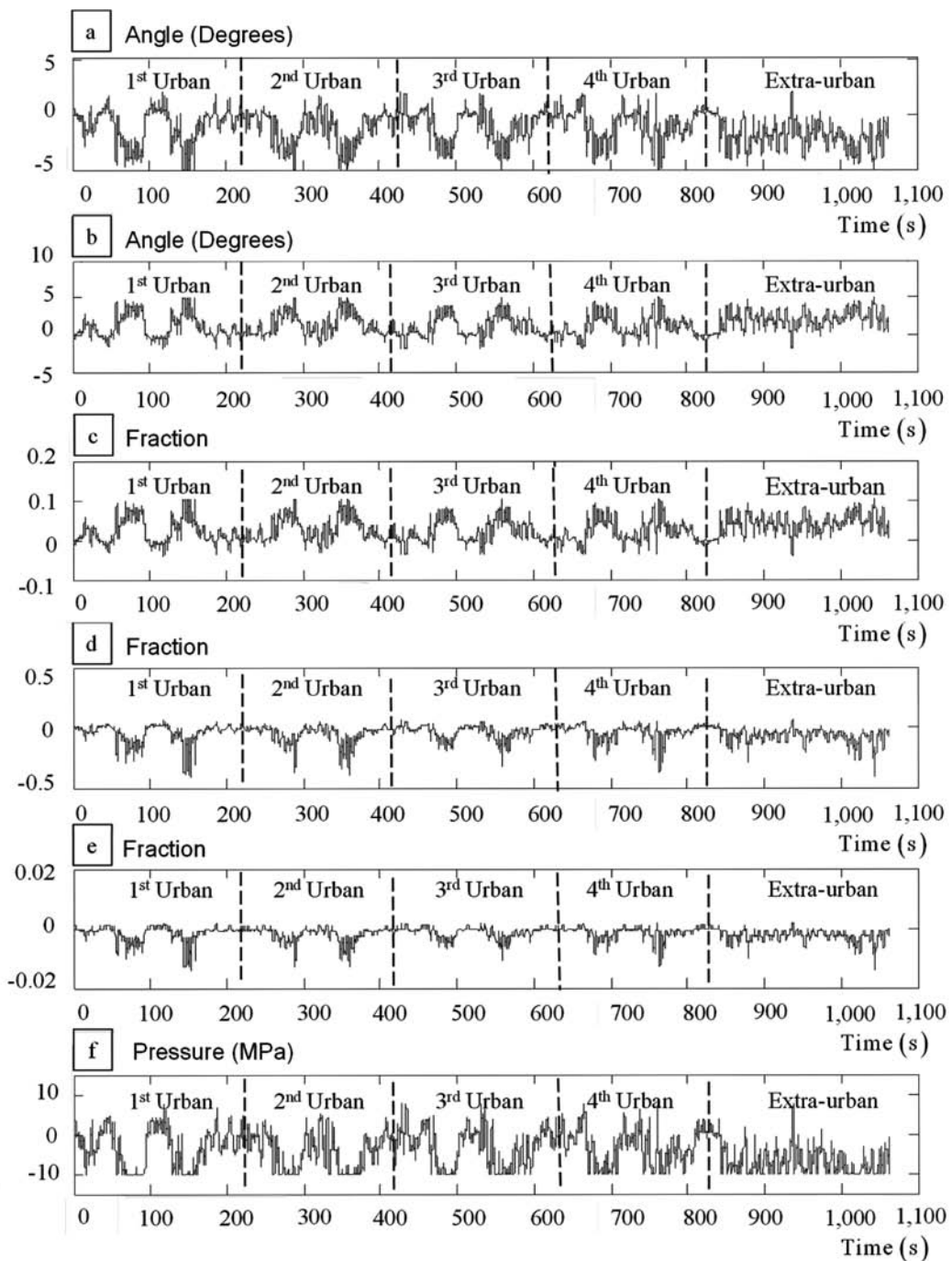


Figure 8 Various Δ set-points of 2nd cylinder for: (a) Pilot start of injection (SOI); (b) Main SOI; (c) Replacement; (d) Total fuel; (e) Fuel split; (f) Rail pressure.

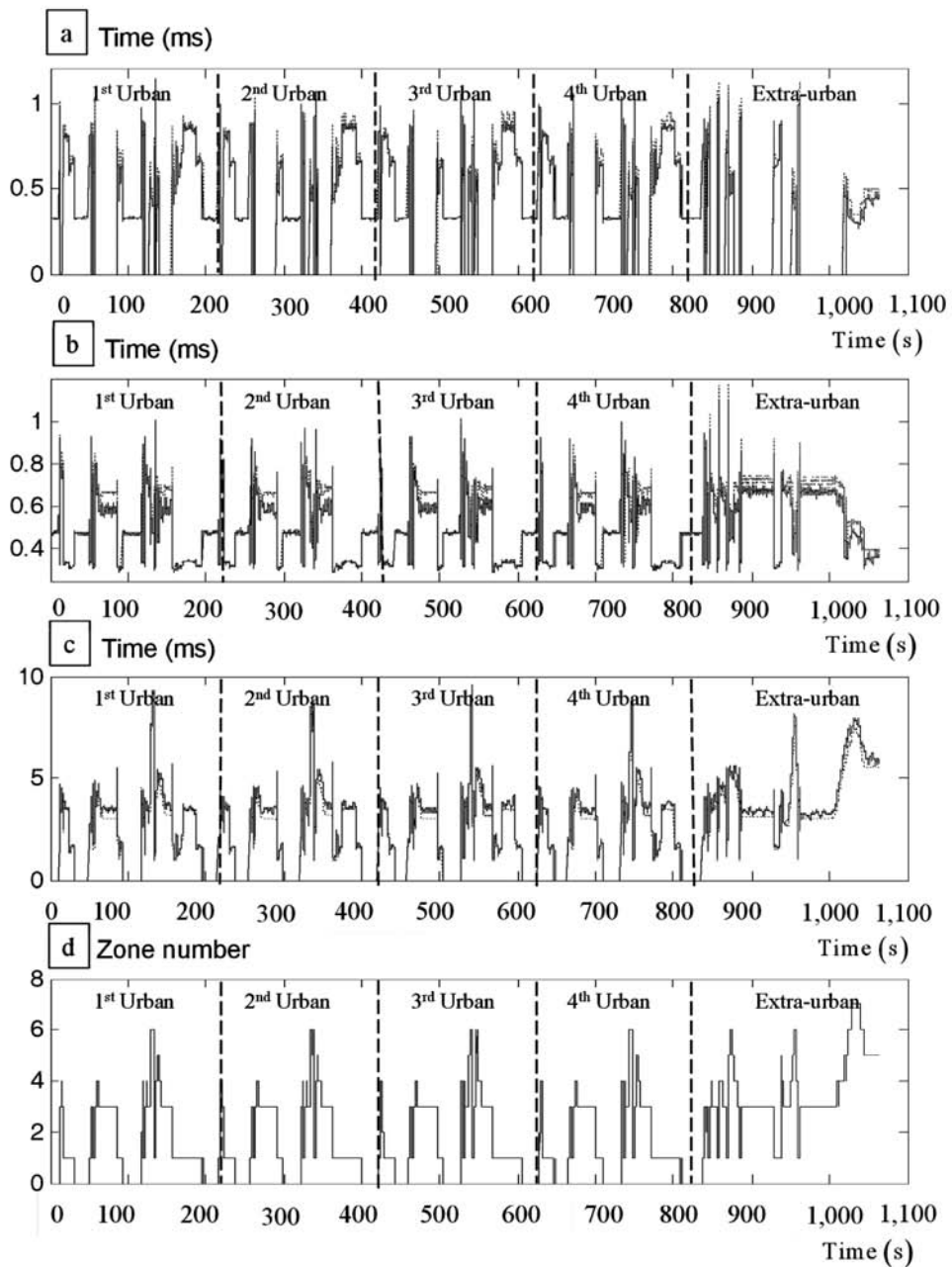


Figure 9 Duration results for (a) Pilot duration, 2nd cylinder; (b) Main duration, 2nd cylinder; (c) Compressed natural gas duration, 2nd cylinder; (d) Zone number.

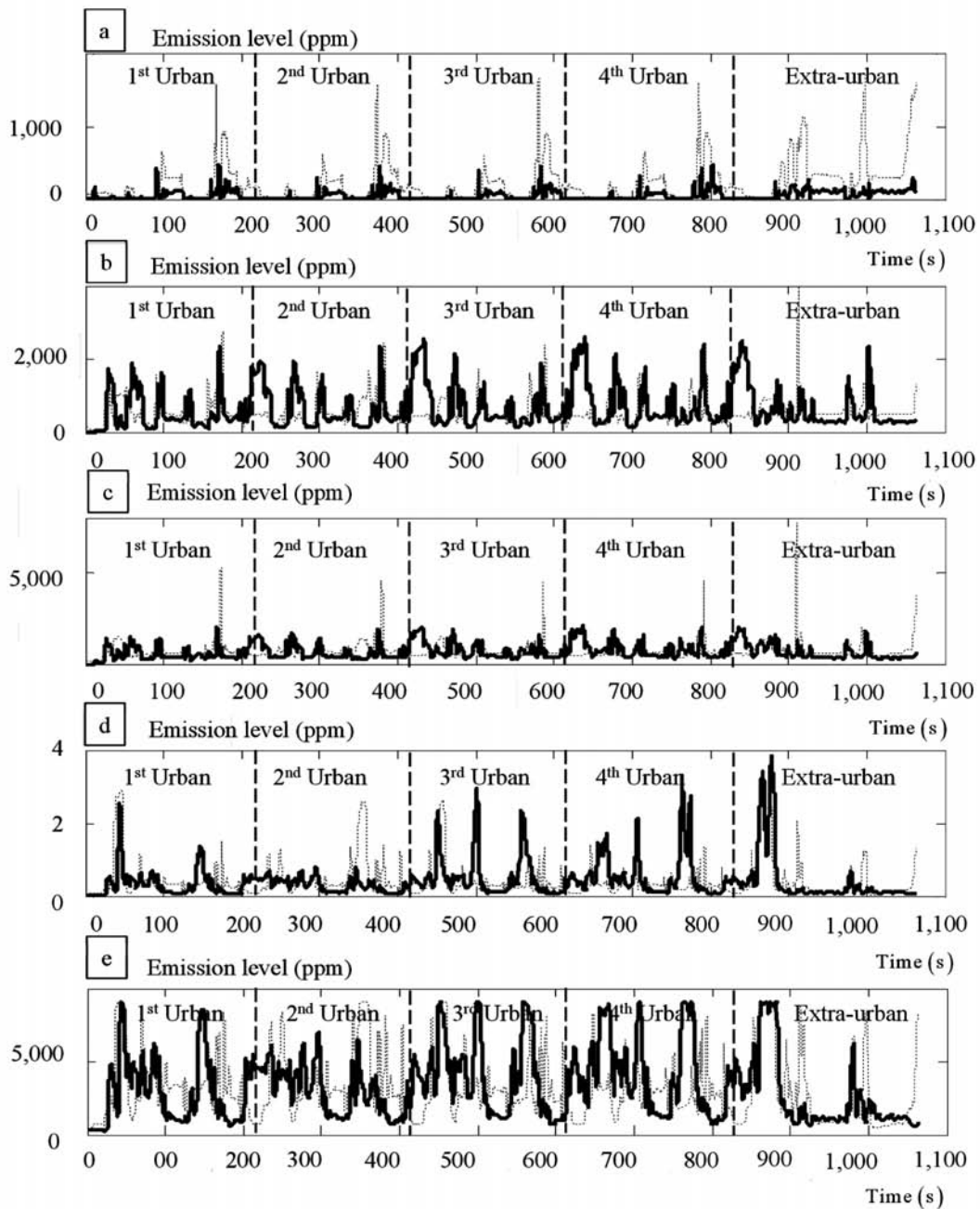


Figure 10 Emission levels in parts per million (ppm) for: (a) No_x ; (b) CH_4 ; (c) Total hydrocarbon emissions; (d) CO_{HIGH} ; (e) CO_{LOW} . The solid lines are with knock control and the dotted lines are without.

In the future, the fuzzy supervisory controller will be programmed on a programmable engine control module (ECM) sourced from Woodward Inc., Fort Collins, CO, USA by using Matlab & Simulink, Real-Time Workshop computer software (Natick, MA, USA). The ECM has been proven to be a commercial product in terms of price and performance. However, the catalytic converter system should be able to treat the emissions to regulation levels before installation of the diesel-dual-fuel engine into a commercial vehicle.

Air path actuators such as a throttle, an EGR valve and a variable nozzle turbine can also be controlled to achieve better performance which includes knock reduction. Advanced control systems can enhance the performance of the tracking control of the actuators and of the idle speed control of the engine. Learning more about such control procedures will provide further information that can help address the uncertainty of engine wear.

ACKNOWLEDGEMENTS

The authors acknowledge the technical and financial support of the PTT Research and Technology Institute, PTT Public Company Limited.

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