

An Application of Model Based Combustion Control to Transient Cycle-by-Cycle Diesel Combustion

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ABSTRACT

From the viewpoint of the global warming restraint, reduction of exhaust emissions from diesel engine is urgent demand. However, it needs further development in combustion control besides after treatment system. Larger amount of EGR (Exhaust Gas Recirculation) is effective to reduce NO_x emission. On the other hand, in-cylinder physical conditions greatly influence on self-ignition and combustion process, especially low O₂ fraction charged gas owing to excessive EGR causes misfire. A drastic solution for this problem, fuel injection timing should be optimally manipulated based on predicted ignition delay period before actual injection.

For this purpose, Toyota has developed a model based diesel combustion control concept to avoid the misfire and to keep low emission combustion includes in transient condition. The feed-forward self-ignition timing controller consists of the intake gas O₂ fraction estimation model, the ignition timing prediction model, and the fuel injection timing finding function. On each cycle, the ignition timing prediction model makes a relational expression between fuel injection timing and predicted ignition timing. And the injection timing finding function finds the required injection timing to meet self-ignition timing to its target by using the expression. In the experiment, the controller prevents the transient excessive ignition delay, and the torque response and HC emission is improved. As a consequence, the control concept has been realized as a practical on-board control technology.

INTRODUCTION

In recent days, from the viewpoint of the controlling global warming, diesel vehicles have become very popular because of their excellent fuel economy. In order for diesel vehicles to be more widely accepted, reduction of exhaust emission from diesel engine has become an urgent issue. To reduce nitrogen oxides (NO_x) and particulate matter (PM) from diesel engines, various after treatment technologies are being proposed, and

synergistic effects of these technologies with in-cylinder combustion process is effective.

Exhaust Gas Recirculation (EGR), where a part of exhaust gas is re-circulated into intake gas, is effective in reducing NO_x generation in combustion process. Therefore recent combustion technology employs a large amount of EGR. However, when there is an excessive or insufficient amount of intake air or EGR gas due to transient turbo-charging delay or limitation in the EGR flow control speed, the combustion state can deviate from the ideal condition.

An engine system is composed of components having differing response speeds. These range from a turbo-charger with slow response, to fuel injection with variable control for each cycle. Given this background, this study establishes a comprehensive control system for turbo-chargers, EGR, and in-cylinder combustion that is capable of controlling the physical condition influencing combustion and emissions in a quick and responsive manner. The aim is also to confirm the effectiveness and practicality of this control system.

THE OVERALL STRUCTURE OF DIESEL COMBUSTION CONTROL

Figure 1 shows the typical diesel engine. Intake air is supercharged with a Variable Geometry Turbocharger (VGT) capable of adjusting boost pressure via a variable nozzle, and after cooling the air down with an intercooler, it is introduced into cylinders while being mixed with EGR gas. EGR gas is also cooled down to avoid the increase of intake temperature. Fuel is injected multiple times with high pressure in and around the top dead center, and the injection pattern is calibrated to control emissions and combustion noise.

Figure 2 shows general response speeds of the main components. An increase in torque is required in a fraction of a second in order to satisfy the driver's expectations for the acceleration response. The air intake response lags behind by a few seconds, and the target due to the inertia of the VGT. The change of

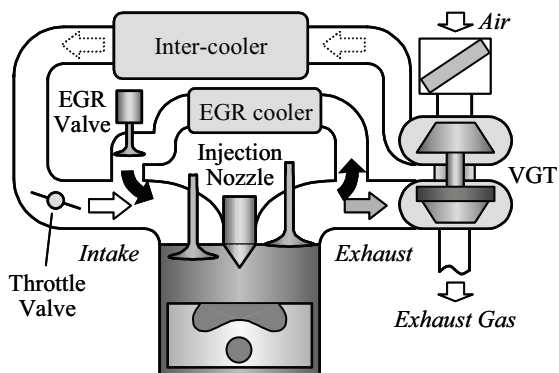


Figure 1 Diesel Engine System Configuration

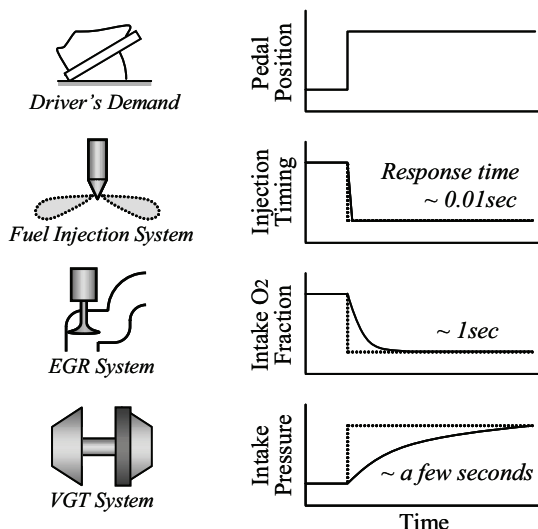


Figure 2 Typical Response Speed of Main Components

intake gas O₂ fraction is limited by the response of the EGR system, and it reaches the target in approximately one second. The combustion that generates the torque and emissions can be controlled for each cycle in a fuel injection pattern. However, the combustion process itself is influenced by the physical conditions inside the cylinder, such as the O₂ fraction, the amount charged gas, temperature of charged gas and so on.

Figure 3 shows the basic structure of the overall control system, organized according to the response speeds of combustion, EGR, and the turbo-charging system. The control input is the torque requirement based on the driver's operation, and the output is the torque and emissions generated from the combustion process. As already mentioned above, the engine system has certain factors which prevent an immediate response to the demands of the driver, but the torque generation should preferably be taking place without any rate-limitation due to these low speed elements. So, in this control system, a layered structure was adopted wherein each control layer compensates for any control error in the in-cylinder physical conditions occurring in layers having slower response than its own. In this way the limitations imposed on the entire system by the time lag in each control element can be functionally minimized.

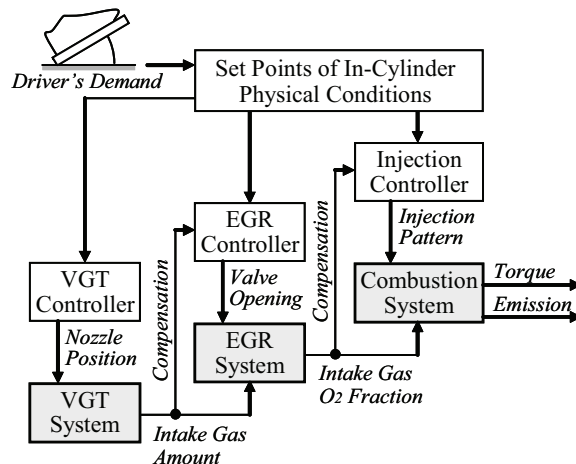


Figure 3 The Total Engine Control System Structure

CONTROL OF THE INTAKE AIR BY THE VGT

Figure 4 shows control of the intake air pressure by the VGT. Due to the inertial mass of the turbo charger, the intake air pressure has the slowest response of the physical conditions that change with respect to driver operation. Therefore, in an effort to achieve the target air intake pressure based on engine speed, load, engine's warm-up condition, atmospheric conditions, etc., the VGT nozzle opening is manipulated and the precision is enhanced by means of feedback control using the air intake pressure sensor. Figure 5 shows the air intake pressure and exhaust pressure during acceleration. When maximizing closed loop control gain and closing the nozzle excessively for the purpose of reducing the delay in turbo-charging, a rise in exhaust pressure

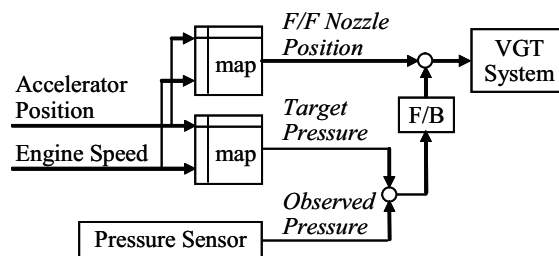


Figure 4 Intake Pressure Control by a VGT

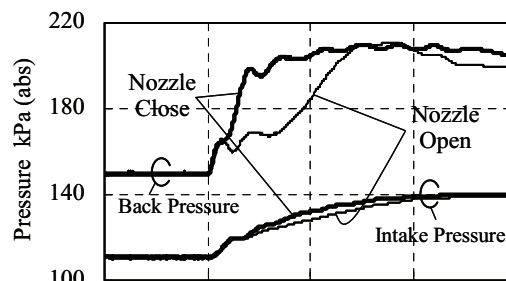


Figure 5 Steep Increase of Back Pressure Caused by Closing VGT Nozzle to Reduce Supercharging Delay

occurs that considerably deteriorates the fuel consumption, and provides only a small improvement in the response of the turbo-charger. Therefore, it is necessary to compensate for this with EGR or fuel injection control so as to minimize the delayed effect of turbo-charging on torque and emissions.

CONTROL OF THE INTAKE GAS O₂ FRACTION WITH EGR

EGR is a very important control element which determines the intake gas composition and has a faster response than the supercharging. The effect of EGR is to mix the inert gas in the exhaust gas with the intake gas and to reduce the O₂ fraction in the intake gas. Therefore, the inert gas can be used to reduce the flame temperature (5), while also controlling the generation of NO_x (Figure 6). In the EGR control layer, the ratio of fresh air amount vs. EGR gas in the total intake gas amount that controlled in the VGT layer, namely, the EGR ratio is regulated. Since there is a trade-off between NO_x and PM, the EGR has to be precisely controlled and therefore the control system mentioned below has been developed.

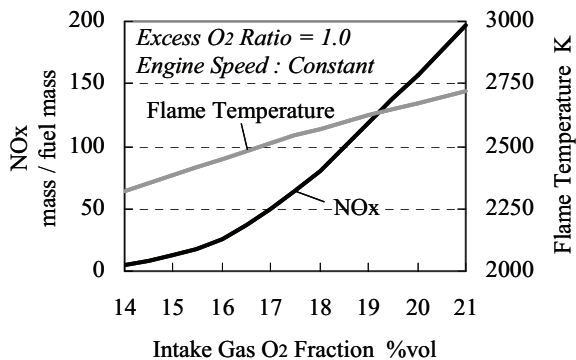


Figure 6 Flame Temperature and NO_x Based on O₂ Fraction

CLOSED LOOP CONTROL VIA THE AIR FLOW RATE SENSOR

The EGR amount changes due to tolerances of the EGR system component parts, resulting in differences in the amount of NO_x emission. Changes in the EGR flow rate are expressed as changes in the intake air amount at steady state. Based on this concept, a constant air controller shown in Figure 7 has been developed. This is a closed loop control which observes the intake air amount via a flow rate sensor and controls it to the calibrated set point value at a given engine speed and load using EGR and air throttle valves. In other words, this is an excess air ratio control wherein the air is controlled against the load. Figure 8 indicates the relation between the excess air ratio, intake gas O₂ fraction, and NO_x amount. Even if the excess air ratio is constant, the intake gas O₂ fraction changes according to boost pressure, and therefore the amount of NO_x also changes.

Consequently, it has been found that keeping the excess air ratio at a target value is not the best strategy for controlling NO_x emission.

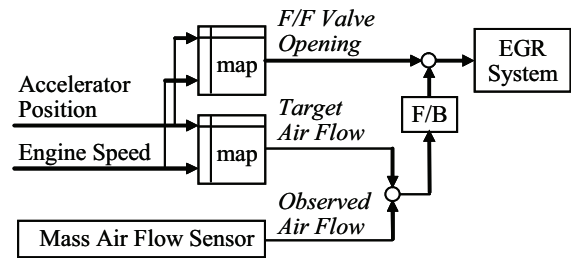


Figure 7 Conventional Air Flow Based EGR Control

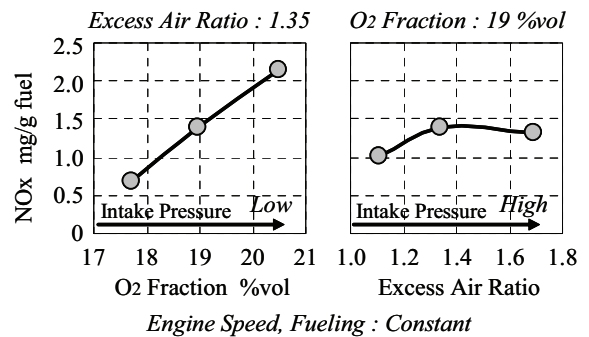


Figure 8 NO_x Dependency on Intake Gas O₂ Fraction

IMPROVEMENT IN THE PRECISION OF NO_x CONTROL VIA INTAKE GAS O₂ FRACTION CONTROL

Nowadays, increase in boost pressure is being promoted in response to the steep demands for better fuel economy via downsizing, as well as reduction of emissions. In the case of the aforementioned air constant controller, the intake air amount is controlled by highly responsive EGR valves and the EGR amount is adjusted by the VGT which has a slower response, and therefore when the turbo-charging is delayed, the EGR amount becomes insufficient and NO_x increases. As mentioned already, since the amount of NO_x is strongly correlated to the O₂ fraction of intake gas, if the change in the intake gas O₂ fraction during the delay in turbo-charging is compensated for by EGR control, then control of NO_x is possible. Accordingly, we developed an intake gas O₂ fraction controller.

In the case of the intake gas O₂ fraction, it has been found that, from the standpoint of controllability, it is desirable to control it by using the EGR ratio which can be observed with a shorter delay than the intake gas O₂ fraction itself. (The primary reason is described in the chapter 5.1.1.) In the previous research, we found the intake gas O₂ fraction being able to be expressed by the relational expression based on EGR ratio and excess air ratio (Expression 1). Figure 8 shows the result of the intake gas O₂ fraction calculated by the expression. Though the measured

values are slightly small compared with the calculated results, it seems to be caused by the cohesion of moisture in the gas sample route. Considering above, the results show very good agreement with measured values.

$$\text{Intake Gas O}_2 \text{ Fraction} = \frac{\text{Air O}_2 \text{ Fraction}}{\left(1 - \frac{\text{Observed EGR Ratio}}{\text{Excess Air Ratio}}\right)}$$

Expression 1 Fukuma's Intake Gas O₂ Fraction Expression

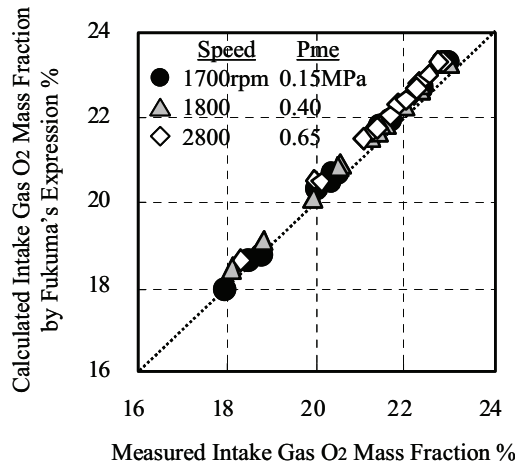


Figure 8 O₂ Fraction Estimation by Fukuma's Expression

The target EGR ratio to control intake gas O₂ fraction is calculated by the expression 2. The EGR ratio is obtained using several sensors and estimation models (1), (2).

$$\text{Target EGR Ratio} = \left(1 + \frac{\text{Standard Intake Air Amount}}{\text{Observed Intake Gas Amount} \times \text{Standard EGR Ratio}}\right)^{-1}$$

Standard : Value in Steady State Condition

- The target is derived from following simultaneous equations

$$\begin{cases} \text{EGR Ratio} = \frac{\text{Observed Excess Air Ratio}}{\text{Standard Excess Air Ratio}} \times \text{Standard EGR Ratio} \\ \text{Intake Gas Amount} = \text{Intake Air Amount} + \text{EGR Gas Amount} \end{cases} \quad \text{(from Expression 1)}$$

Expression 2 Target EGR ratio for the O₂ Fraction Control

Figure 9 shows NO_x emission, the intake gas O₂ fraction, and the air intake pressure in the European driving cycle in comparison with the steady-state values at the corresponding engine speed and load. Under air

constant control, the intake gas O₂ fraction and NO_x increased during the delay in turbo-charging, but under the intake gas O₂ fraction controller, it was possible to control the amount of NO_x and keep it to a level near the steady-state value. Since intake gas O₂ fraction control can control NO_x at the steady state value, optimization of NO_x in an actual vehicle has been made easier.

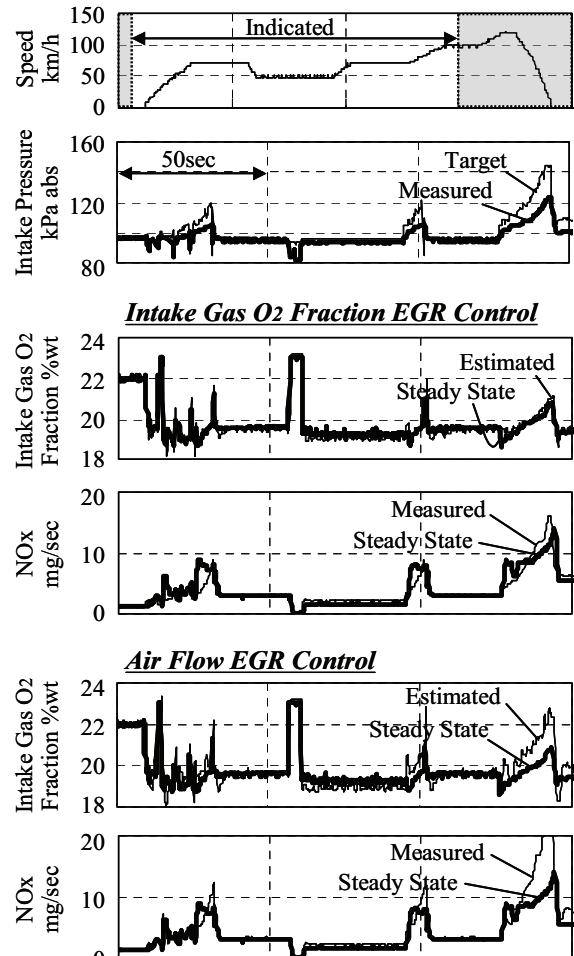


Figure 9 Comparison of NO_x Controllability in Transient Driving Condition

CYCLE-BY-CYCLE COMBUSTION CONTROL

Due to the introduction of Diesel Particulate Filter (DPF) systems capable of reducing PM emissions, when it comes to combustion technology, application of much larger EGR has been studied for the purpose of further NO_x reduction (3), (4). Figure 10 shows the changes in combustion along with the increase in EGR. Excessive EGR can extend the ignition delay period from injection to ignition, and consequently it can cause a misfire which has not been observed in the conventional diesel engines. Changes in the intake gas O₂ fraction during the delay in turbo-charging can be compensated for with the EGR control mentioned above. However, it cannot keep up with quicker demands from the driver due to the