

Achievement of Enhanced Fuel Economy via i-VTEC Intake Valve Closure Delay Mechanism

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ABSTRACT

The conventional VTEC system has been modified with a mechanism enabling delayed closure of the intake valves as a new method of increasing fuel economy. The major characteristic of the new engine is the achievement of a balance between low fuel consumption and high power by means of switching between a delayed closure cam with delayed intake valve closure timing and a high output cam, depending on engine load. The intake valve closure delay mechanism employs the delayed closure cam when the engine is under low load in order to reduce pumping loss. The high output cam is employed when the engine is under high load, in order to produce high power. A variety of driving conditions were considered and in-cylinder flow simulations were used in setting the valve timing of the delayed closure cam. The delayed closure cam achieves a 6% reduction in engine fuel consumption compared to the high output cam. The application of the new VTEC mechanism has enabled the achievement of 17.0 km/L fuel economy in the Japanese 10-15 mode, representing a 5% increase on the level as stipulated by domestic 2010 fuel economy standards.

1. Introduction

Against a background of increasing concern about the environment, enhancing the environmental performance of automotive engines by increasing fuel economy and reducing emissions has become an important issue in the engine development process. CO₂ emissions can be reduced and fuel economy increased by increasing theoretical thermal efficiency, reducing pumping loss and reducing friction. Honda has worked to enhance environmental performance by developing lean-burn and direct cylinder injection engines⁽¹⁾ and by combining its VTEC system with a mechanism for continuous camshaft phase variation to produce a 4-cylinder i-VTEC engine⁽²⁾. Honda has also developed a V6 i-VTEC⁽³⁾ engine fitted with a variable cylinder system allowing cylinder idling.

Delaying closure of the intake valves to increase the expansion ratio to greater than the compression ratio is known to be one approach to increasing thermal efficiency. This approach is

discussed in the technical literature as the Atkinson and Miller cycles⁽⁴⁾⁻⁽⁶⁾, and has been applied in a number of engines^{(7),(8)}.

As indicated, delayed closure of the intake valves is an effective method of increasing fuel economy. However, the longer valve closure is delayed to increase efficiency, the greater the decline in charging efficiency and consequent decline in power at high-load, high-engine speeds necessitating the use of a turbocharger or a hybrid mechanism.

Honda has developed an innovation on this design in the R18A 1.8L 4-cylinder gasoline engine. The R18A engine has been provided with an i-VTEC mechanism that switches between normal and delayed closure of the intake valves to balance low fuel consumption, high power and low exhaust emissions⁽⁹⁾. In the development process, the effect of the intake valves' delayed closure on pumping loss and combustion stability and the mechanism's effectiveness in enhancing fuel consumption were examined.

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2. Intake Valve Delayed Closure

2.1. Effect on Thermal Efficiency

Figure 1 shows a comparison of the P-V diagrams of a conventional (Otto cycle) engine and an engine using an intake valve delayed closure mechanism.

In conventional engines, the compression and expansion ratios are almost identical. When closure of the intake valves is delayed, however, an over-expanded cycle is produced, in which the actual air-fuel mixture compression ratio in the intake stroke (the effective compression ratio) and the expansion ratio in the expansion stroke differ. An engine using this cycle has a higher thermal efficiency than Otto cycle engines do at the same compression ratio.

The thermal efficiency of the Otto cycle and over-expanded cycle engines as shown in Fig. 1 can be expressed as follows:

Otto cycle engine:

$$\eta_o = 1 - \frac{1}{\epsilon_o^{\kappa-1}} \quad (1)$$

Where: Compression ratio $\epsilon_o = V_{o1}/V_{o2} = V_{o4}/V_{o3}$
Specific heat capacity ratio κ

Over-expanded cycle engine:

$$\eta_e = 1 - \frac{\beta \epsilon_e^{1-\kappa} \epsilon_e^{\kappa} + \kappa (\epsilon_e' - \epsilon_e) - \epsilon_e'}{\epsilon_e^{\kappa(\beta-1)}} \quad (2)$$

Where: Effective compression ratio $\epsilon_e = V_{e1}/V_{e2}$
Expansion ratio $\epsilon_e' = V_{e4}/V_{e3}$
Degree of explosion $\beta = P_{e3}/P_{e2}$

Figure 2 shows the results of thermal efficiency calculations using Eqs. (1) and (2) when the expansion ratio is set at 10.5. The effective compression ratio varies in the case of the over-expanded cycle engine and the compression ratio varies in the case of the Otto cycle engine. The degree of explosion was set at 4.5 on the basis of engine tests. These results indicate that the expansion ratio determines changes in thermal efficiency. At the same compression ratio, an engine with a high expansion ratio would display superior fuel economy. In addition, the lower effective compression ratio in the over-expanded cycle reduces the temperature in the cylinders during compression, which could be expected to reduce heat loss and prevent knocking.

2.2. Effect on Pumping Loss

When a gasoline engine is under low loads, the throttle valve is normally restricted to reduce air flow. When the engine is operating in this state, air is taken in under negative pressure, causing pumping loss. Figure 3 shows a diagrammatic representation of the

difference in pumping loss between a conventional engine and an engine using delayed closure of the intake valves. As shown in (b), using a delayed closure cam for the valve closure causes some of the air that is taken in during the intake stroke to reenter the intake manifold in the first half of the compression stroke, changing the actual compression commencement point from A to A'. This enables air flow to be adjusted with less restriction of the throttle valve, which reduces pumping loss.

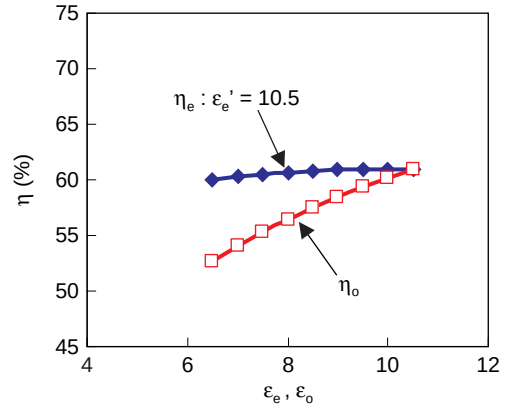


Fig. 2 Influence of ϵ_e and ϵ_o on cycle efficiency

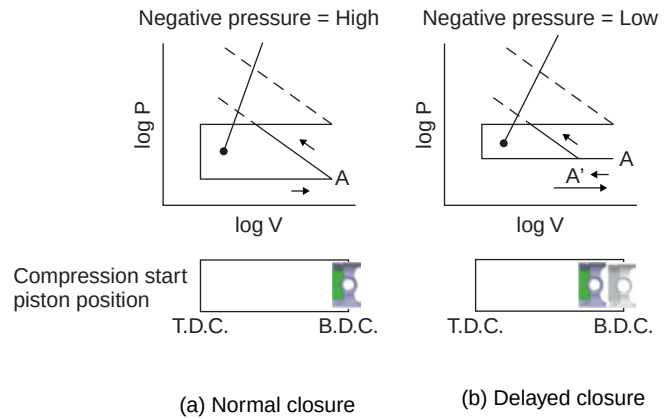


Fig. 3 Influence of intake valve closure timing on pumping loss

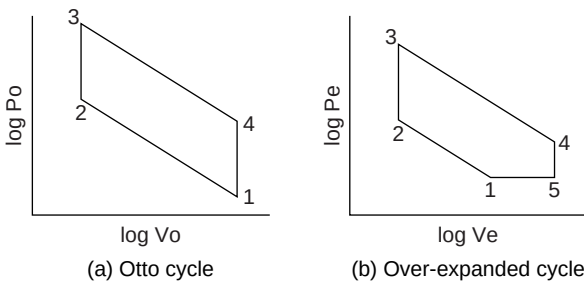


Fig. 1 Comparison of P-V diagram between Otto cycle and Over-expanded cycle

3. Test Equipment

Table 1 shows the main specifications of the R18A i-VTEC test engine.

The test engine used two intake valves, one of which was operated by switching between the high output and delayed closure cams. Different delayed closure cams with a variety of valve closure timings were used in the tests. Valve lift for intake valve opening and closing timing was set at 1 mm. Figure 4 shows the various intake valve closure (I.V.C.) timings used for the high output and delayed closure cams and the cam profiles.

Table 1 Engine specifications

Type	R18A
Cylinder configuration	In-line 4-cylinder
Bore × Stroke (mm)	81 × 87.3
Displacement (cm ³)	1799
Compression ratio	10.5:1
Valve train	SOHC i-VTEC Inlet delayed closure
Number of valves	4 per cylinder
Valve diameter (mm) In./Ex.	32/26
Cylinder offset (mm)	12
Intake manifold	Variable intake system
Gasoline	Regular (RON91)
Max. power (kW/rpm)	103/6300
Max. torque (Nm/rpm)	174/4300

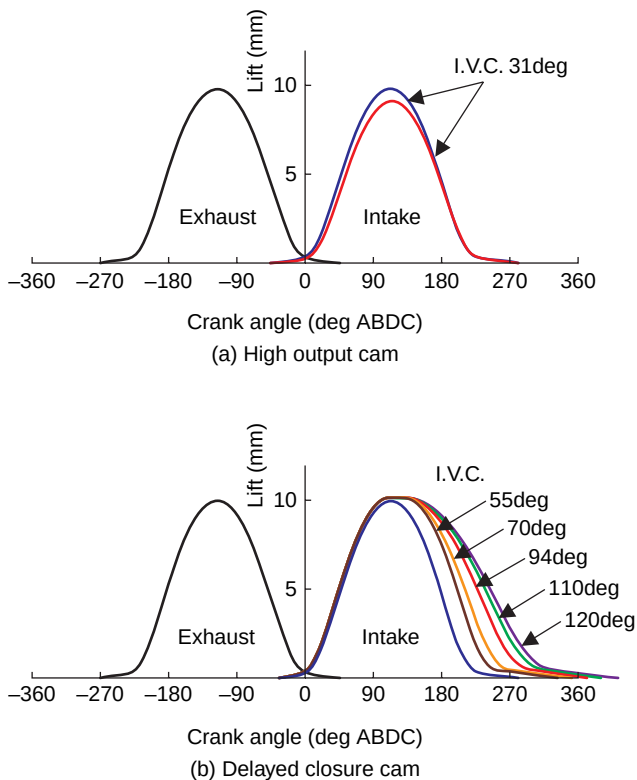


Fig. 4 Applied I.V.C and cam profiles

The pressure waveform is based on samples taken at every 1 deg of crank angle using a pressure sensor (Kistler 6052B) and a charge amp (Kistler 5011B).

4. Results and Observations

4.1. Effect of Delayed Closure Cam on Pumping Loss

Figure 5 shows a pressure diagram for the high output and delayed closure cams at the same output. The I.V.C. was 31 deg (ABDC) for the high output cam and 94 deg for the delayed closure

cam. In the case of the delayed closure cam, air was returned to the intake manifold in the first half of the compression stroke, delaying the commencement of compression. In addition, the average negative pressure during the intake stroke was closer to atmospheric pressure, and pumping loss was reduced.

Figure 6 shows the ratio of the volumetric efficiency (η_v) of the high output and delayed closure cams at wide-open throttle, defined as the intake air reduction rate. When the delayed closure cam was operating, 25-35% of the intake air was returned to the intake manifold, reducing the apparent displacement. Switching between cams as required via the i-VTEC mechanism balanced high power during high loads with reduced fuel consumption during low loads.

4.2. Effect of Delayed Closure Cam on Thermal Efficiency

Figure 7 shows the effect on the indicated specific fuel consumption (ISFC) rates of I.V.C. of 31, 94 and 120 deg. A gross figure that includes a fraction for pumping loss has been used for the indicated mean effective pressure (IMEP)⁽¹⁰⁾.

Because the compression ratio of the test engine was set at 10.5, the ISFC values do not change significantly with changes in the I.V.C., but there is approximately a 0.5% reduction in the case of the delayed closure cam. This is believed to be because the change

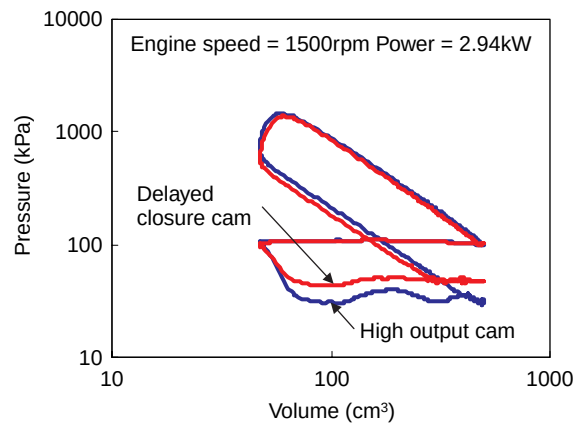


Fig. 5 Effect of delayed closure inlet valve timing for reduction of pumping loss

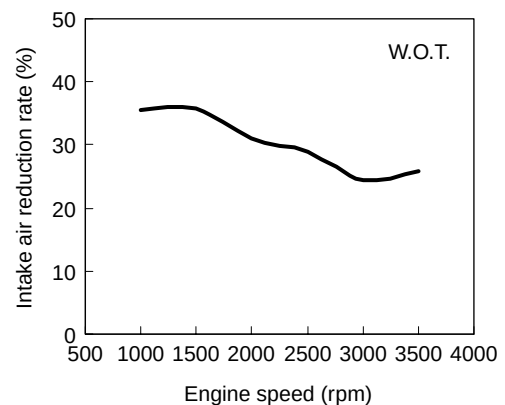


Fig. 6 Intake air reduction rate at inlet valve delayed closure

in the effective compression ratio has reduced the temperature in the cylinders, thus reducing heat loss to the cylinder walls. When the IMEP is increased, at an I.V.C. of 31 deg there is an area in which knocking causes an ignition timing lag and the ISFC increases. At an I.V.C. of 94 deg, however, knocking does not occur and there is no increase in the ISFC, even at wide-open throttle. However, the IMEP declines at wide open throttle with increasing delay in the I.V.C.

4.3. Effectiveness of Delayed Closure Cam in Enhancing Fuel Economy

Figure 8 shows the effect of the I.V.C. on pumping loss, brake-specific fuel consumption (BSFC) and co-variation of the IMEP.

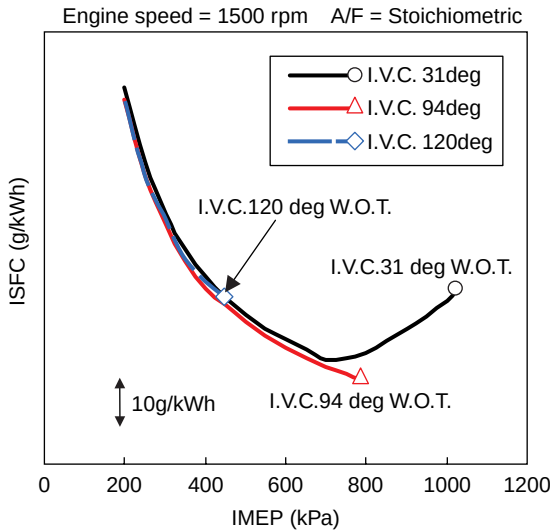


Fig. 7 Influence of I.V.C. on ISFC

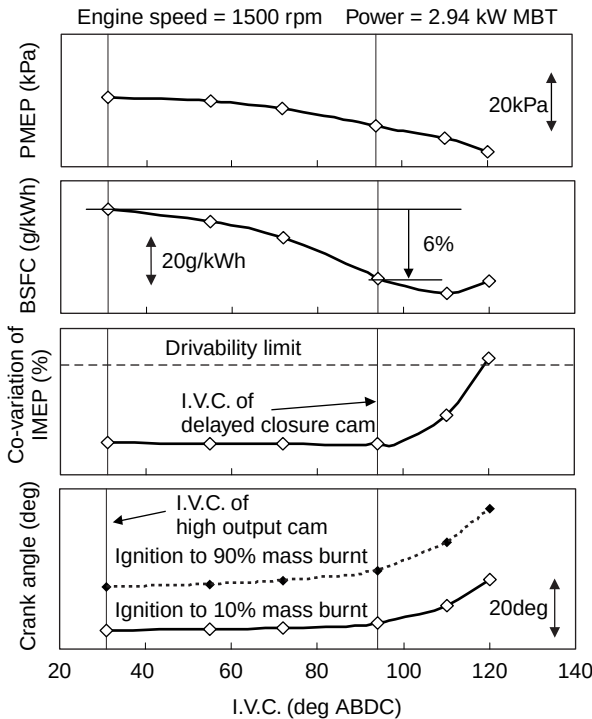


Fig. 8 Influence of I.V.C. on PMEP, BSFC, characteristics of combustion

Pumping loss declines and BSFC decreases with increasing delay in the I.V.C., but after 110 deg there is no further decrease in BSFC, despite the fact that pumping loss continues to decline. This is thought to be because excessive delay in the I.V.C. causes in-cylinder flow attenuation and a reduction in the temperature in the cylinders, resulting in slow initial post-ignition combustion, which cancels the effect of reduced pumping loss⁽¹¹⁾.

Figure 9 shows the results of a simulation of the in-cylinder turbulence energy and fuel distribution in the second half of the compression stroke. Comparing the energy of turbulence around the spark plug for the high output cam (I.V.C. 31 deg) and the delayed closure cam at an I.V.C. of 94 deg, it is clear that the area of highest energy is fairly narrow at 94 deg. At 110 deg, the energy of the turbulence around the plug declines markedly, and the rich area of the fuel distribution is also reduced in size. This is thought to be the cause of rapid rise in IMEP co-variation, which expresses combustion stability during initial and main combustion. These results indicate that an excessive delay in intake valve closure reduces the energy of in-cylinder turbulence at ignition and produces a lean fuel distribution, causing a change in ignition.

Figure 10 shows the rate of reduction of BSFC for the high output cam (I.V.C. 31 deg) when the I.V.C. is varied under load conditions corresponding to those experienced under standard cruising speeds. At 40 km/h, the reduction in BSFC is maximized at an I.V.C. of 98 deg, but at 80 km/h and above, BSFC does not reach bottom, even when the I.V.C. is delayed to 120 deg. This is thought to be because the decline in in-cylinder turbulence and in-cylinder temperature when the I.V.C. is delayed is greater at low vehicle speeds (low engine speeds, low loads) than at high vehicle speeds (high engine speeds, high loads). The I.V.C. for optimum

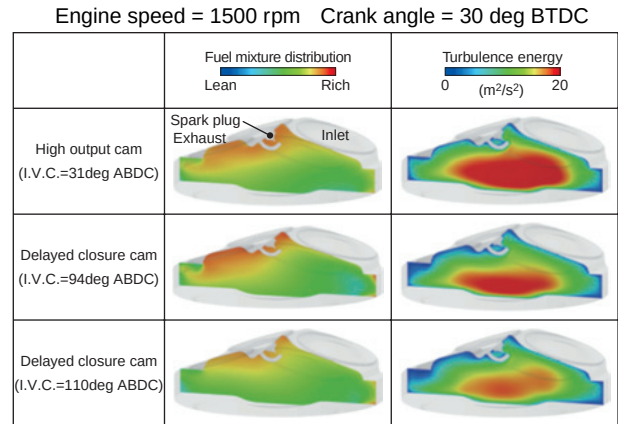


Fig. 9 Comparison of turbulence energy and fuel mixture distribution

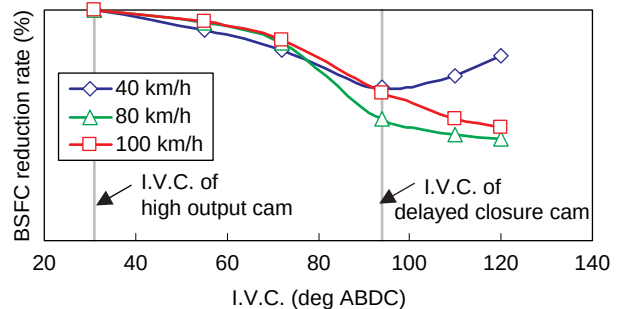


Fig. 10 BSFC reduction rate at cruise condition

BSFC changes as load conditions change. An I.V.C. of 94 deg was selected for the delayed closure cam, taking fuel economy benefits and combustion stability into consideration. This reduced BSFC by 6% against that of the high output cam while ensuring identical combustion stability.

Figure 11 shows co-variation in the IMEP, NO_x emissions and BSFC against the EGR rate. The reduction in fuel consumption with the EGR is higher for the high output cam, but the performance of the delayed closure cam remains superior even when the EGR is introduced.

In terms of combustion characteristics in relation to the EGR rate, the EGR rate limit for stable combustion is lower for the delayed closure cam than for the high output cam, but NO_x emissions for the delayed closure cam at the minimum point of BSFC are identical to those for the high output cam because of the reduction in in-cylinder temperature produced by delayed valve closure.

4.4. Switching Range for Delayed Closure Cam and Enhancement in Fuel Economy

Figure 12 shows a map of the rate of reduction in BSFC for the delayed closure cam against the high output cam. The effectiveness of the delayed closure cam in increasing fuel economy is most apparent at the low engine speed, low load range in which its effectiveness in reducing pumping loss is greatest, but it produces fuel economy benefits across the entire range in which it operates.

In addition to the effect of the delayed closure cam, fuel economy has been further enhanced by the application of technologies to reduce friction, resulting in the achievement of a 17 km/l fuel economy rate in the Japanese 10-15 mode using a vehicle employing the R18A engine.

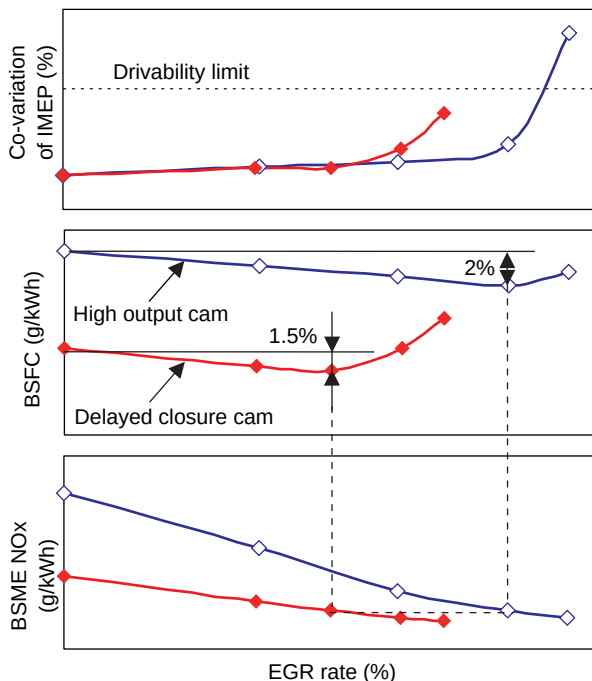


Fig. 11 Comparison of EGR characteristics between conventional valve timing and delayed valve timing

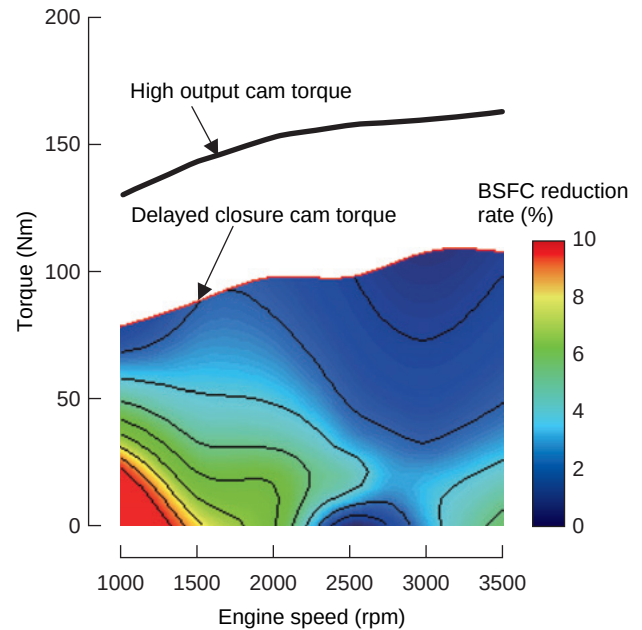


Fig. 12 BSFC reduction rate map (W/O EGR)

5. Conclusion

An i-VTEC mechanism that is able to switch between a high output cam and a cam enabling delayed intake valve closure has been developed. During the development process, the relationship between delay timing and the enhancement of fuel economy was examined. The following are the significant findings of this research:

- (1) Operation of the delayed closure cam produces an over-expanded cycle. At an I.V.C. of 94 deg, BSFC is increased by 6% against that of the high output cam (I.V.C. 31 deg).
- (2) When operation is switched between the high output and delayed closure cams while maintaining the same compression ratio, the enhancement in fuel economy is dependent on the reduction in pumping loss.
- (3) Despite the fact that the delayed closure cam has a lower EGR limit for stable combustion than does the high output cam, their levels of NO_x emissions at the minimum point of BSFC are identical, due to the reduced in-cylinder temperatures produced by delayed closure.

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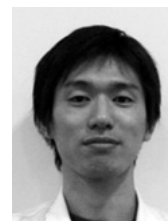
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