

Development of 1.8L CNG Engine for 2006 CIVIC GX

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ABSTRACT

Honda has developed the 2006 CIVIC GX, a natural gas vehicle that it has been mass-producing since 1998. For this model, Honda has developed and fitted a new Compressed Natural Gas (CNG) engine. This new engine was designed to further enhance power. The increased engine displacement and use of a variable-length air intake manifold have achieved a 15% increase in power. In addition, engine fuel consumption has been reduced by 4% through a combination of a reduction in pumping loss due to the inlet valve delayed closure, and a charging stroke injection that harnesses the properties of gaseous fuel. As a countermeasure for tail pipe emissions, a cylinder head integrated with the exhaust manifold and a close-coupled two-bed catalyst have been used. As a result, the amount of precious metal used was reduced by approximately 30%, and is in compliance with the Advanced Technology Partial-Zero Emission Vehicle (ATP-ZEV) Standards. Despite the increased weight of the larger vehicle design, the CIVIC GX achieved a fuel economy increase of 15% in FTP highway mode, and an equivalent fuel economy in combined mode.

1. Introduction

In recent years, various alternative fuels have been examined from the perspective of reducing air pollution. The reduction of carbon dioxide has also become a very important issue from the perspective of reducing global warming. CNG engines are internal combustion engines that have excellent environmental performance, with virtually zero Non Methane Hydro Carbon (NMHC) emissions. Honda launched the CIVIC GX⁽⁴⁾ in 1998 to proactively address environmental issues. The 2001 CIVIC GX (D17A engine)⁽³⁾ was the first in the world to comply with the Advanced Technology Partial-Zero Emission Vehicle (ATP-ZEV) regulations. The new CNG R18A engine was developed for the 2006 CIVIC GX to maintain environmental performance while further enhancing driving performance and fuel economy. This report gives a

description of the fuel economy enhancement technology^{(1),(2)}, which uses inlet valve delayed closure.

2. Development Goals

The development goals for the CIVIC GX CNG engine were to achieve an environmental performance better than that of previous models, and to further enhance driving performance and fuel economy. The specific targets were defined as follows:

- (1) Achieve the best exhaust emission gas performance of internal combustion engines to comply with ATP-ZEV, the strictest regulations in the world
- (2) Increase engine output
- (3) Enhance fuel economy

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3. Outline and Specifications

3.1. CNG Fuel Characteristics

CNG is a gaseous fuel that contains alkanes extracted from oil and gas fields, a small amount of oxygen, and inert components. The primary alkane extract is methane, but others including butane are also used. Table 1 shows the characteristics of gasoline and methane, the main components of CNG. The characteristics of CNG compared to gasoline as an internal combustion engine fuel are as follows:

- (1) An increased Research Octane Number (RON) and a larger compression ratio are required because combustion during partial loads is poor.
- (2) It is a gaseous fuel, so there is a reduction of 10% or more in charging efficiency for the fuel volume.
- (3) It is a gaseous fuel, so the energy density is low.
- (4) Carbon dioxide emissions are reduced by about 30%.

The heating value of an internal combustion engine fuel is the heating value of the charged mixture. The characteristics of methane, the main component, are as follows.

- (1) The heating value by weight is higher than for gasoline.
- (2) The heating value when mixed with air at its stoichiometric ratio is equivalent to the heating value when gasoline is mixed with the same amount of air at its stoichiometric ratio.
- (3) Since there is a reduction of 10% or more in charging efficiency, there is also a similar reduction in the heating value for each cycle.

A comparison with the gasoline heating value is shown in Table 2.

3.2. Engine Outline

Table 3 shows a comparison with the previous D17A CNG engine and with the base R18A gasoline engine. The main changes from the gasoline specifications are as follows.

- (1) Compression ratio change
- (2) Use of a CNG fuel supply system

The main changes from the previous CNG engine are as follows.

- (1) Use of the i-VTEC inlet valve delayed closure valve train to enhance fuel economy
- (2) Use of a variable-length air intake to increase output
- (3) Change to LAF+O₂ A/F control

Figure 1 shows the overall view.

Table 1 Comparison of methane and gasoline fuel characteristics

Fuel		CH ₄	Gasoline
RON		130	91
A/F	Weight	17.2	14.5
	Volume	9.52	8.3 × 10 ³ (Liquid)
Charging efficiency (%)		90.5	100
Exhaust gas at stoich.	CO ₂ (%)	9.5	13.5
	H ₂ O (%)	19.0	12.5

Table 2 Comparison of methane and gasoline heating value

Fuel		CH ₄	Gasoline
Lower heating value	(MJ/kg)	50.1	42.7
	(MJ/air m ³)	3.80	3.80
	(MJ/air+fuel m ³)	3.42	3.80

Table 3 Engine specifications

Engine code	R18A		D17A
Fuel	CNG	Gasoline	CNG
Cylinder configuration	In-line 4-cylinder		In-line 4-cylinder
Bore × Stroke (mm)	81 × 87.3		75 × 94.4
Displacement (cm ³)	1799		1668
Compression ratio	12.5	10.5	12.5
Valve train	SOHC i-VTEC Inlet delayed closure		SOHC VTEC-E 1 intake valve inactive
Number of valves	4 per cylinder		4 per cylinder
Valve diameter (mm)	IN	32	30
	EX	26	26
Cylinder offset (mm)	12		0
Intake manifold	Variable intake system		Conventional
Fuel control	LAF+O ₂ sensor		O ₂ +O ₂ sensor



Fig. 1 R18A i-VTEC CNG engine

4. Fuel Economy Improvement Technology

4.1. Fuel Economy Improvement Effect by Inlet Valve Delayed Closure

Pumping loss reduction technology based on inlet valve delayed closure was introduced for this engine. The aim of this technology is to enhance the fuel economy. Figure 2 shows the conceptual diagrams.

There are three main reasons for the effectiveness of inlet valve delayed closure in improving fuel economy:

- (1) Reduction of pumping loss
- (2) Enhancement of thermal efficiency due to the reduction of the effective compression ratio and the extended expansion ratio
- (3) Reduction of mechanical loss due to a lower cylinder pressure caused by the reduction of the effective compression ratio

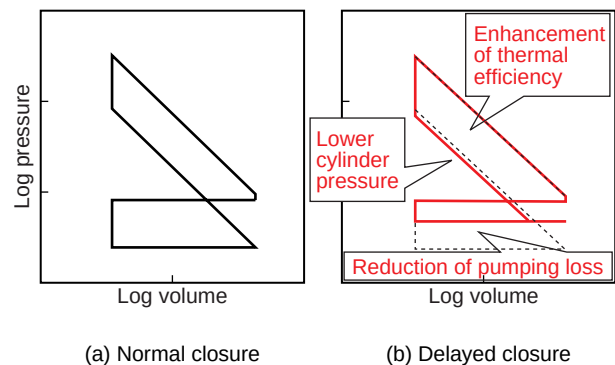


Fig. 2 Comparison of P-V diagram between normal and delayed closure

4.2. Pumping Loss Reduction

The pumping loss is expressed as follows:

$$W_p = \left(\frac{P_{BA}}{k-1} \frac{\epsilon}{\epsilon-1} \right) \left(1 - \left(\frac{1}{\epsilon} \right)^{k-1} \right) - \frac{P \left(\frac{P_{BA}}{P} \right)^{\frac{1}{k}} \frac{\epsilon}{\epsilon-1}}{k-1} \left(1 - \left(\frac{1}{\left(\frac{P_{BA}}{P} \right)^{\frac{1}{k}} \epsilon} \right)^{k-1} \right) + P \left(\left(\frac{P_{BA}}{P} \right)^{\frac{1}{k}} \frac{\epsilon}{\epsilon-1} - \frac{1}{\epsilon-1} \right) - P_{BA} V \quad (1)$$

W_p : Pumping loss

ϵ : Compression ratio

V : Stroke volume

P : Air pressure

P_{BA} : Intake pressure

κ : Specific heat ratio

Here, if the following relationship is assumed,

$$P_{BA_d} = \frac{\epsilon}{\epsilon_d} P_{BA}$$

W_{pd} : Pumping loss during inlet valve delayed closure operation

P_{BA_d} : Intake pressure during inlet valve delayed closure

ϵ_d : Compression ratio during inlet valve delayed closure

Pumping loss during inlet valve delayed closure operation can be expressed as:

$$W_{pd} = \left(\frac{\epsilon}{\epsilon_d} \frac{P_{BA}}{\epsilon-1} \right) \left(1 - \left(\frac{1}{\epsilon} \right)^{k-1} \right) - \frac{P \left(\frac{\epsilon}{\epsilon_d} \frac{P_{BA}}{P} \right)^{\frac{1}{k}} \frac{\epsilon}{\epsilon-1}}{k-1} \left(1 - \left(\frac{1}{\left(\frac{\epsilon}{\epsilon_d} \frac{P_{BA}}{P} \right)^{\frac{1}{k}} \epsilon} \right)^{k-1} \right) + P \left(\left(\frac{\epsilon}{\epsilon_d} \frac{P_{BA}}{P} \right)^{\frac{1}{k}} \frac{\epsilon}{\epsilon-1} - \frac{1}{\epsilon-1} \right) - \frac{\epsilon}{\epsilon_d} P_{BA} V \quad (2)$$

When Eqs. (1) and (2) are compared, it can be seen that the pumping loss reduction ratio during inlet valve delayed closure operation is determined by the effective compression ratio and intake pressure.

4.3. Thermal Efficiency Enhancement Due to Extended Expansion Ratio

This section will examine the thermal efficiency⁽⁵⁾ of the extended expansion ratio cycle caused by the inlet valve delayed closure. The thermal efficiency of a regular Otto cycle is:

$$\eta = 1 - \left(\frac{1}{\epsilon} \right)^{k-1}$$

η : Thermal efficiency

The thermal efficiency during inlet valve delayed closure operation is expressed as follows.

$$\eta_d = 1 - \left(\frac{1}{\epsilon} \right)^{k-1} + \frac{T_a C_v}{Q} \left(1 - \left(\frac{\epsilon_d}{\epsilon} \right)^{k-1} \right)$$

η_d : Thermal efficiency during delayed closure operation

Q : Heating value

T_a : Intake temperature

C_v : Specific heat at constant volume

The thermal efficiency ratio is expressed as follows.

$$\frac{\eta_d}{\eta} = 1 + \frac{T_a C_v}{Q} \frac{1 - \left(\frac{\epsilon_d}{\epsilon} \right)^{k-1}}{1 - \left(\frac{1}{\epsilon} \right)^{k-1}}$$

This is a slightly increased thermal efficiency. Figure 3 shows the results of the calculation. If the ratio of the effective compression ratio and the compression ratio is 0.7, then the thermal efficiency is increased by 1.5%.

4.4. Mechanical Loss Reduction

The reduction of the effective compression ratio due to inlet valve delayed closure operation lowers the cylinder pressure, and so is effective in reducing mechanical loss. The cylinder pressure ratio is expressed as:

$$\frac{P_{cd}}{P_c} = \left(\frac{\epsilon_d}{\epsilon} \right)^k$$

P_c : Pressure after compression

P_{cd} : Pressure after compression during delayed closure operation

This is a reduction. This is likely to reduce mechanical loss in areas such as the bearings.

The characteristics of inlet valve delayed closure operation are summarized below:

- (1) Reduction of pumping loss
- (2) Increase in thermal efficiency
- (3) Reduction of mechanical loss
- (4) Reduction of effective compression ratio
- (5) Reduction of charging efficiency

The above are determined by the delayed Inlet Valve Closure (I.V.C.). As a result, a thermal efficiency increase effect is achieved through the pumping loss reduction. Also, a mechanism that compensates for the accompanying reduction in charging efficiency is needed.

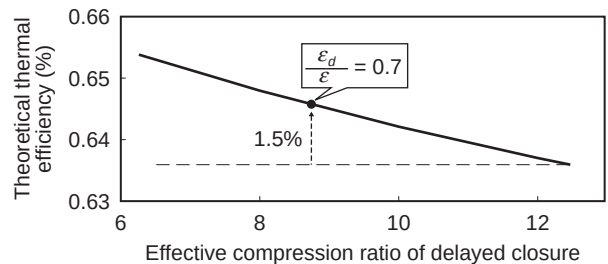


Fig. 3 Comparison of theoretical thermal efficiency between conventional and delayed valve timing

4.5. i-VTEC Inlet Valve Delayed Closure Mechanism

This engine uses Variable Valve Timing and Lift Electronic Control (VTEC) to achieve both high output and inlet valve delayed closure operation. In conditions such as acceleration, which require high output, the inlet valve is activated with a cam that generates the maximum output (this is referred to as high output cam). When the engine load is light, such as during cruising, the engine switches to a cam that delays the closure timing of one of the inlet valves (this is referred to as delayed closure cam). At the same time, pumping loss is reduced by opening the electric control throttle, which improves the fuel economy. The i-VTEC mechanism integrates control of this electric control throttle and VTEC, and enables the engine to switch optimally between the high output cam and delayed closure cam in accordance with the driving conditions.

Figure 4 shows the i-VTEC inlet valve delayed closure valve train. The i-VTEC switching is performed by connecting and separating the rocker arm, through the hydraulic movement of the synchro piston built into it. In this engine, the switching mechanism is only used in one of the rocker arms in two inlet valves.

When the high output cam operates, synchro piston B is moved hydraulically, which disconnects synchro piston A, and activates the inlet valve with cam profile A.

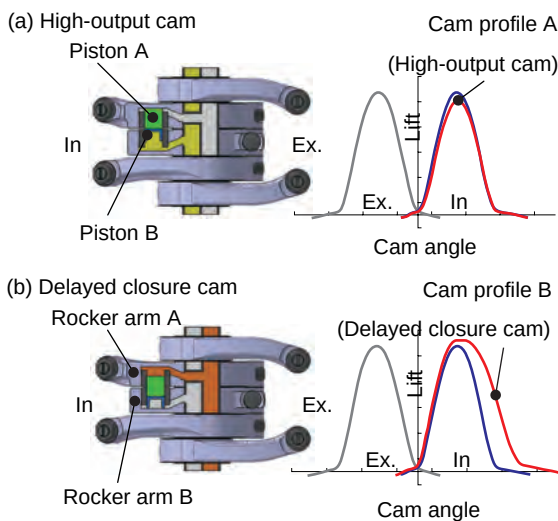


Fig. 4 Rocker arm and cam profile

5. Engine Performance

5.1. Determining the Delayed I.V.C.

It is preferable to delay the I.V.C. as much as possible from the perspective of minimizing pumping loss. On the other hand, the delay is accompanied by a reduction in output. This reduces the operable range with delayed closure and increases the switching frequency. As a result, a delayed closure compression ratio must be determined that delivers the required output for the upper limit of engine speed when cruising.

The delayed closure operating range for this engine has been set so that the speed upper limit during normal use is 120 km in 5th, and the required output is 130% of output when cruising. These settings are equivalent to those in the gasoline specifications of this engine. The delayed closure cam I.V.C. uses the following to estimate the output change from the actual gasoline measurements:

- (1) Reduced charging efficiency due to CNG injection
- (2) Heating value
- (3) Compression ratio change

As shown in Fig. 5, the estimate is 86 degrees, which is earlier than the 94 degrees for gasoline.

The BSFC reduction rate ratio in this case is estimated to be about 5%, compared to about 6% for gasoline. The results of the test show that the output is approximately equal to the assumed value, but that the BSFC reduction rate is lower than the value assumed from the pumping loss reduction. Figure 6 shows the BSFC and ISFC changes for each load. It verifies that the ISFC is increased when the load is low. The reason a result equivalent to gasoline was not obtained may be that the 10% to 90% mass burnt during the delayed closure was too long. An analysis of this reason is performed below.

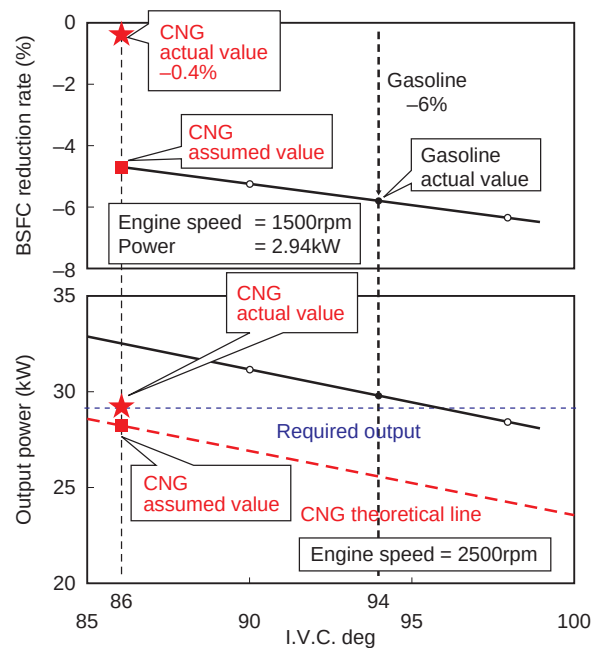


Fig. 5 Relationship between I.V.C. and output power and charging efficiency

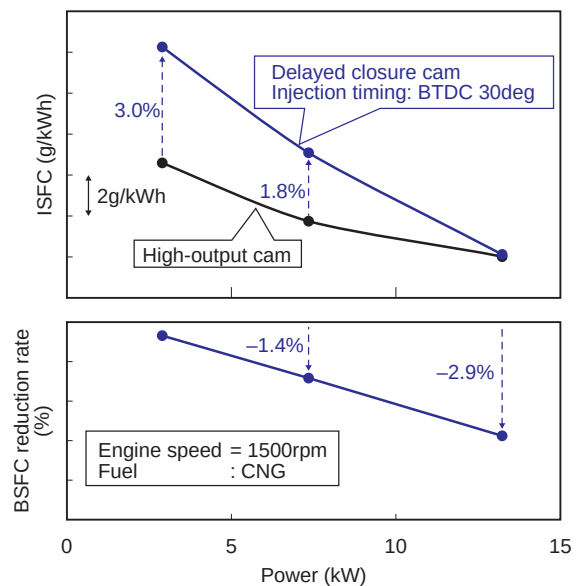


Fig. 6 Comparison of ISFC between conventional and delayed valve timing

5.2. Fuel Economy Improvement for Delayed Closure Operation

Figure 7 and Table 4 show a comparison of the mass burnt ratio between CNG and gasoline combustion with the high output cam. The compression ratio for CNG increases from 10.5 to 12.5, so that the main 10% to 90% mass burnt (Mass Burnt Fraction 10 - 90%) is approximately equivalent to that of gasoline.

Figure 8 and Table 5 show a comparison of the mass burnt ratio for CNG between the high output cam and the delayed closure cam. With the delayed closure cam, it is likely that the main 10% to 90% mass burnt will be extended and the thermal efficiency decreased. As shown by Fig. 9 and Table 6, when the delayed closure operation is performed with gasoline, the extension of the main 10% to 90% mass burnt is short. To enhance the ISFC, it is likely that a shortening of the 10% to 90% mass burnt during delayed closure operation will be required.

As a method for shortening the main 10% to 90% mass burnt, a flow increase was attempted in this engine by harnessing the characteristics of gaseous fuel injection. Figure 10 shows the relationship between injection timing and BSFC. By combining the delayed closure with the charging stroke injection, it was possible to verify a BSFC reduction of about 5%. However, it was not possible to verify a BSFC reduction with the high output cam.

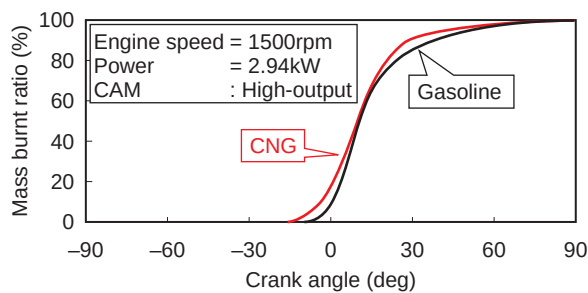


Fig. 7 Comparison of mass burnt ratio between CNG and gasoline

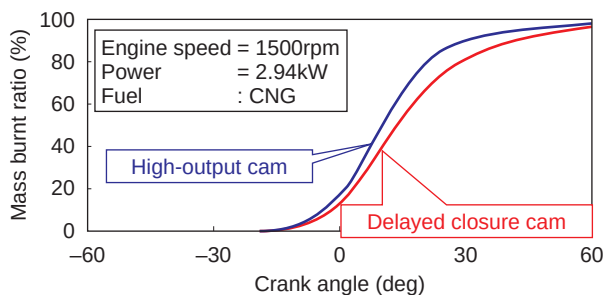


Fig. 8 Comparison of mass burnt ratio between conventional and delayed valve timing

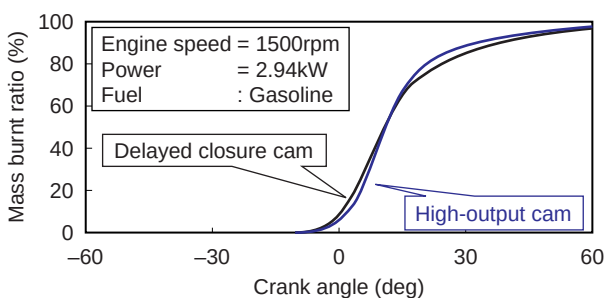


Fig. 9 Comparison of mass burnt ratio between conventional and delayed valve timing

Table 4 Comparison of IG to 10% mass burnt and 10% to 90% mass burnt between CNG and gasoline

Fuel	CNG	Gasoline
IG to 10% mass burnt (deg.)	33	38
10% to 90% mass burnt (deg.)	33	30

Table 5 Comparison of IG to 10% mass burnt and 10% to 90% mass burnt between conventional and delayed valve timing

Fuel	CNG	
Inlet closure	High-output	Delayed
IG to 10% mass burnt (deg.)	33	40
10% to 90% mass burnt (deg.)	33	43

Table 6 Comparison of IG to 10% mass burnt and 10% to 90% mass burnt between conventional and delayed valve timing

Fuel	CNG		Gasoline	
Inlet closure	High-output	Delayed	High-output	Delayed
Injection timing	Exhaust	Exhaust	Exhaust	Exhaust
IG to 10% mass burnt (deg.)	33	40	38	46
10% to 90% mass burnt (deg.)	33	43	30	37

Figure 11 and Table 7 show the mass burnt ratio in order to verify from the combustion that the BSFC has been enhanced. In the exhaust stroke injection, it was verified that the main 10% to 90% mass burnt that was extended by about 10 degrees was shortened by about 8 degrees, and it was understood that it recovered to a main 10% to 90% mass burnt approximately equivalent to the high output cam. It was understood that even in comparison with gasoline, the 10% to 90% mass burnt extension was shorter for the CNG charging stroke injection. Figure 12 shows the reduction effect for BSFC and ISFC when combined with charging stroke

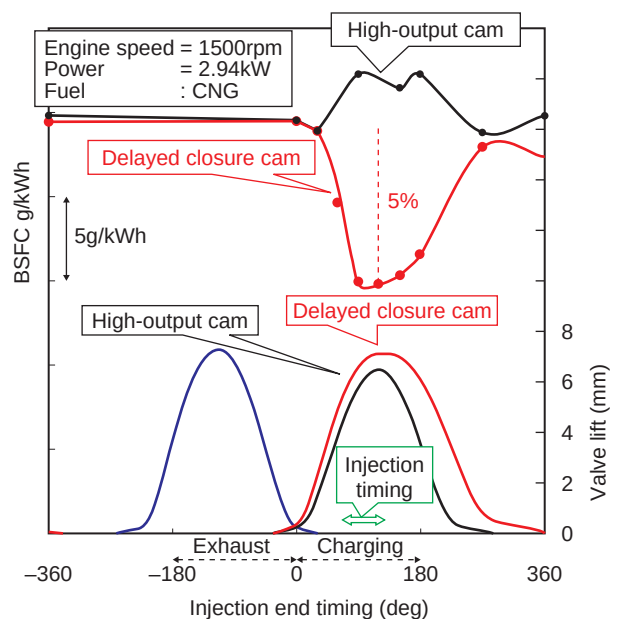


Fig. 10 Comparison of injection timing characteristics between conventional and delayed valve timing

injection. It was verified that by combining the delayed closure with the reduced charging stroke injection ISFC, a BSFC reduction equivalent to the predicted value was obtained.

Possible reasons for the enhancement are as follows:

- (1) The kinetic energy of the fuel injection that reaches the speed of sound at the injection nozzle is converted to the activation of the flow inside the cylinder.
 - (2) The 10% to 90% mass burnt was shortened by stratifying the mixture and making it richer in the vicinity of the spark plug.
- These are issues to be examined in the future.

5.3. Actual Measurement Results for Pumping Loss and Mechanical Loss

Figure 13 shows the relationship between intake negative pressure and motoring friction when the engine speed is 1500 rpm. Even with the same intake pipe negative pressure, there are differences in the motoring friction values between the high output cam and the delayed closure cam. This is likely to be because the mechanical loss in areas such as the bearings was reduced. This reduction was due to the lowering of the cylinder pressure during the compression stroke, caused by the reduction in the effective compression ratio. Figure 14 shows the motoring friction under the conditions of 1500 rpm and 2.94 kW. As shown by Table 8, the BSFC reduction effect due to friction reduction caused by the delayed closure cam was about 3.5%. It can be estimated that the

Table 7 IG to 10% mass burnt & 10% to 90% mass burnt

Fuel	CNG		Gasoline	
	High-output	Delayed	High-output	Delayed
Inlet closure	High-output	Delayed	High-output	Delayed
Injection timing	Exhaust	Charging	Exhaust	Exhaust
IG to 10% mass burnt (deg.)	33	40	38	46
10% to 90% mass burnt (deg.)	33	35	30	37

Table 8 Comparison of friction between conventional and delayed valve timing

	Power (kW)	Friction (kW)	Indicated power (kW)	BSFC reduction (%)
High-output cam	2.94	3.18	6.12	—
Delayed closure cam	2.94	2.97	5.91	3.5

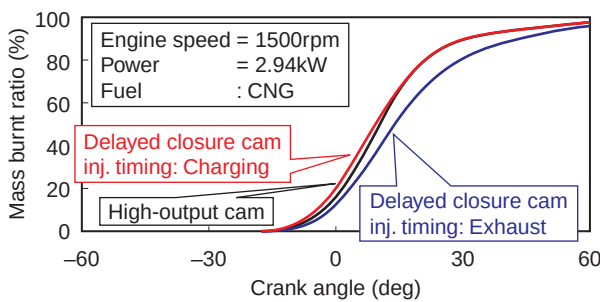


Fig. 11 Comparison of mass burnt ratio between conventional and delayed valve timing

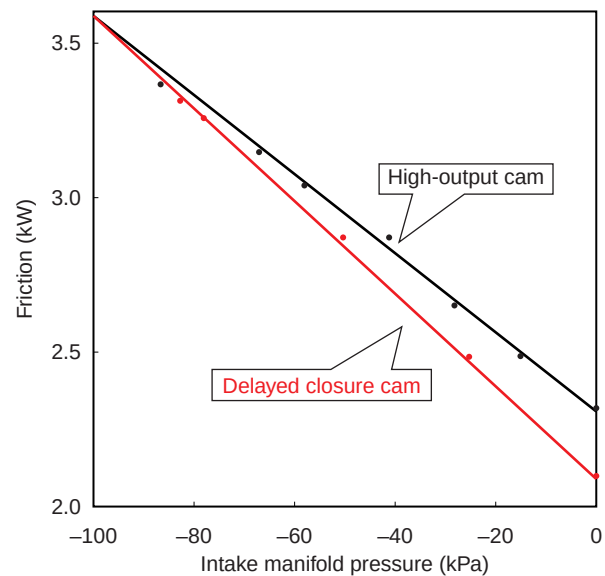


Fig. 13 Comparison of friction between conventional and delayed valve timing

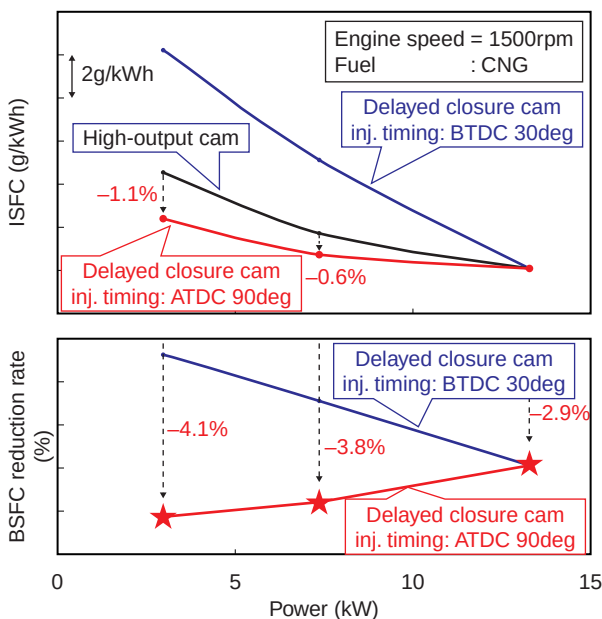


Fig. 12 Comparison of SFC between conventional and delayed valve timing

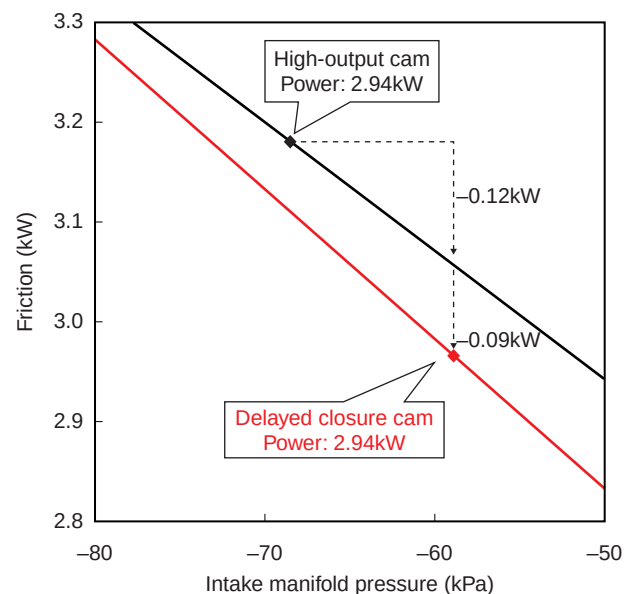


Fig. 14 Comparison of friction between conventional and delayed valve timing

effect of the pumping loss reduction due to the increase in throttle angle is about 2%. It was verified that by performing inlet valve delayed closure operations, a motoring friction reduction was achieved that exceeded the effect from the pumping loss reduction.

5.4. Engine Performance

This engine uses a new variable-length air intake manifold as shown in Fig. 15. An increase in the charging efficiency is achieved by closing the bypass valve in low to medium speed ranges and opening it in high speed ranges. Figure 16 shows the output characteristics for a wide open throttle. As shown in Table 9, there was an increase of 7% in the converted output value for engine displacement. Combined with the 8% increase in the engine displacement, this made a 15% increase in output.

As shown in Fig. 17, an excess output of 30% or greater was achieved for the output with delayed closure when the vehicle speed was 120 km/h or less. This means that delayed closure operations are possible for cruising up to 120 km/h and for slow acceleration. This enhances the fuel economy while driving and increases the product appeal.

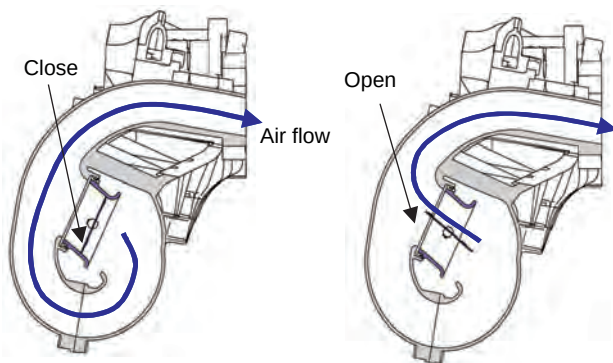


Fig. 15 Motion of bypass valves

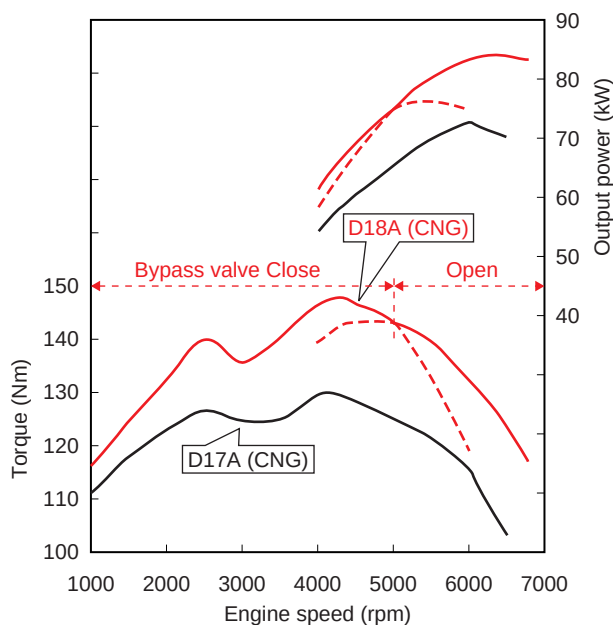


Fig. 16 Engine performance

Table 9 Comparison of engine power between D18A and D17A

	D18A (CNG)	D17A (CNG)
Max. power (kW/rpm)	84/6300	73/6000
Max. torque (Nm/rpm)	148/4300	130/4200

5.5. Actual Vehicle Performance

5.5.1. Exhaust emission performance

The 2006 model uses a cylinder head that is integrated with the exhaust manifold and close-coupled two-bed catalyst, and this is shown in Fig. 18. By concentrating the catalytic converter in a close-coupled position where a high temperature can be maintained, the catalyst precious metal amount is reduced by 30% compared to the previous model. This achieves exhaust emission levels that comply with the ATP-ZEV regulations.

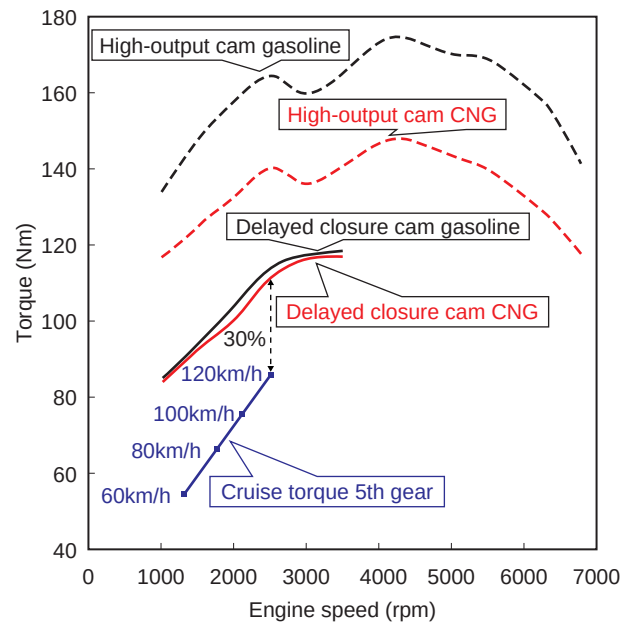


Fig. 17 Operating region of delayed closure cam

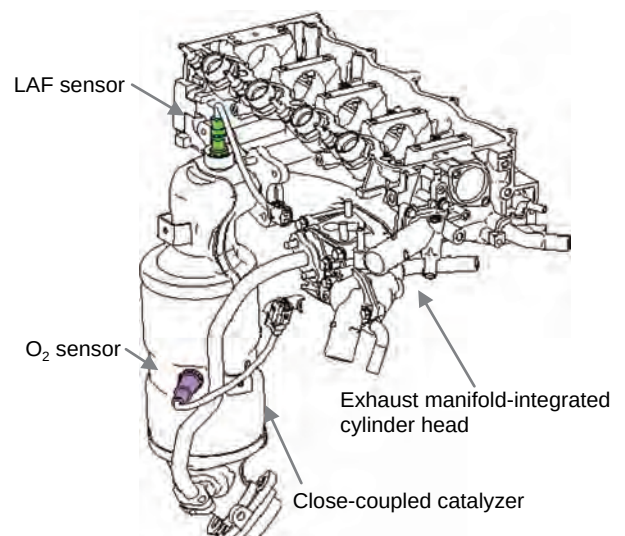


Fig. 18 Exhaust and catalytic converter system

5.5.2. Achieved fuel economy values

In addition to the previously mentioned fuel economy enhancement effect of delayed closure, the use of a variable-length air intake increases the maximum torque by 14%. This creates a high transmission ratio, and lowers the engine speed during cruising to enhance the fuel economy. Table 10 shows the achieved fuel economy values for the 2006 and 2001 models. The fuel economy values in the table for CNG are values converted to a gasoline equivalent (GGE: Gasoline Gallon Equivalent). For a comparison of driving conditions, Fig. 19 shows FTP city mode, and Fig. 20 shows highway mode. The delayed closure frequency is a high 55% in highway mode, where cruising is frequent. Despite the increased weight accompanying the larger vehicle design, a fuel economy enhancement of 15% was achieved. Even in combined mode, a fuel economy equivalent to the 2001 model was achieved.

Table 10 Achieved fuel economy of NGV (Label FE)

	Label FE (mile/GGE)				
	City	HWY	Comb	I.W. (lb)	Transmission
2006 model	28	39	32	3250	5AT
2001 model	30	34	32	3000	CVT

6. Conclusion

A CNG engine was developed that uses a variable valve train with inlet valve delayed closure. Cause analysis was performed to enhance the thermal efficiency. As a result, the increase in the 10% to 90% mass burnt during low loads that accompanies the reduction in the effective compression ratio was enhanced with charging stroke injection.

The following technical enhancements have been achieved in comparison with the 2001 model.

- (1) An enhancement in engine fuel economy of 4% has been achieved. This was done by reducing the pumping loss with inlet valve delayed closure, and by enhancing combustion through charging stroke injection that harnesses the characteristics of gaseous fuel.
- (2) Output for engine displacement has increased by 7% compared with the 2001 model engine, and when combined with the additional engine displacement amount there is a total output increase of 15% compared with the previous model.
- (3) As a countermeasure to reduce exhaust emissions, a cylinder head integrated with the exhaust manifold and a close-coupled two-bed catalyst are used. This also reduces the amount of precious metal by 30% and achieves compliance with the ATP-ZEV regulations.
- (4) Despite the increased weight accompanying the larger vehicle design, a fuel economy enhancement of 15% was achieved in highway mode, and a fuel economy equivalent to the previous model was achieved in combined mode.

7. Afterword

CNG is likely to be useful not only as a countermeasure for emissions, but also for reducing carbon dioxide which is a major contributor to global warming. Such countermeasures have been increasingly used worldwide in recent years. In addition, vast amounts of methane hydrate reserves have been confirmed. The household charging machines launched in 2005 are likely to address the issue of the low number of charging facilities. In the future we aim to further spread the engine among general users, and take action to enhance its appeal as a product.

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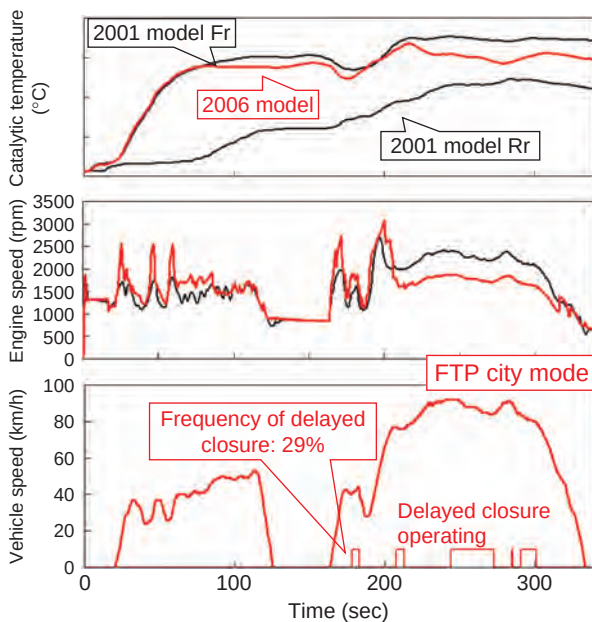


Fig. 19 Engine speed and catalyst temperature during FTP city mode

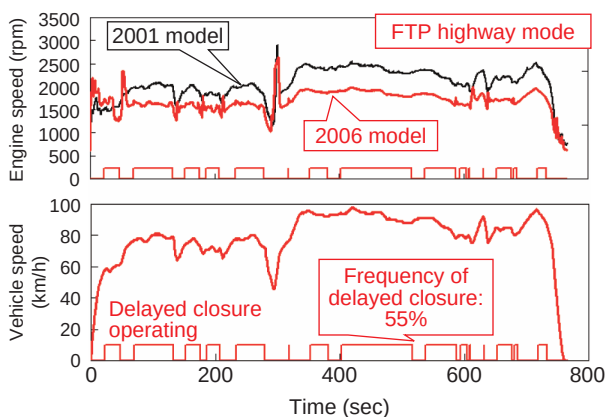


Fig. 20 Engine speed during FTP highway mode

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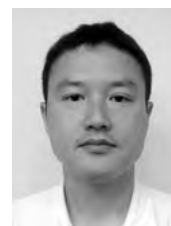
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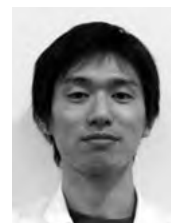
Osamu WATANABE



Toshihide MATSUNAGA



Hiroaki NAKASHIMA



Masahiro NAKAJIMA