

Development of 1.8L Flexible Fuel Vehicle System for 2007 Model Year CIVIC for Brazil

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ABSTRACT

Honda has developed a 1.8L VTEC 4-cylinder engine for a Flexible Fuel Vehicle (FFV) that meets the needs of the Brazilian market. This engine has a function that enables it to be run on either gasoline or ethanol, or on both fuels mixed in any ratio. Engine specifications that are suitable for Brazilian fuel were selected by optimizing the valve timing using VTEC and changing the compression ratio. For the fuel system parts, materials with ethanol corrosion resistance were chosen and applied to the Brazilian market. In this paper, the performance achieved by this engine and the applied technology are described.

1. Introduction

There has been growing demand in recent years for reduced CO₂ emissions to address the issue of global warming. Consequently, the use of biofuels, which are renewable, is capturing increasing attention. As alternatives to gasoline, there are bio-ethanol fuels made from sugar cane, corn, etc., and as alternatives to diesel, there are bio-diesel fuels made from soybean, rapeseed, and so on. Raw material for the bio-ethanol used in Brazil and some other places comes from sugar cane or similar plant life. These plants absorb CO₂ as they grow. The CO₂ emission that results from their use as motor vehicle fuel, therefore, is treated as zero. Biofuels are gaining attention as an alternative to petroleum, and at the same time, as a countermeasure against global warming.

The volume of sugar cane produced in Brazil is high, and there are numerous bio-ethanol manufacturing plants. National policy has, so far, dictated the sale of bio-ethanol fuels. The gasoline that is sold in Brazil needs to have a mixture of 20–25% ethanol (hereafter referred to as gasohol) but fuel composed only of ethanol (hereafter referred to as E 100) is also for sale.

Honda has been selling the CIVIC GX^{(1), (2), (3)} since 1998, which is an alternative fuel vehicle running on natural gas. The new model CIVIC⁽⁴⁾ that went on sale in 2005 has been used as the base vehicle for a flex-fuel engine that was developed for the CIVIC FFV. This paper describes the technology adopted for the CIVIC FFV.

2. Development Goals

In Brazil, the CIVIC with this engine installed is a key model, and it sells at a level second to the Fit. The following development goals were defined in order to meet user needs as a vehicle capable of using both gasohol and ethanol, and to support the diversification of energy sources:

- (1) That there be flexibility in selecting the fuel to be used.
- (2) That the vehicle offers guaranteed driving performance that is not determined by the fuel used.
- (3) That the vehicle offers commercial product appeal in terms of refueling.

3. Fuel Properties

Table 1 shows the typical properties of the main fuels. The commonly distributed fuels in Brazil include gasohol and E 100. One general advantage of ethanol as a fuel for internal combustion engines is its high octane value (RON 110). This makes it possible to increase the compression ratio, so that the thermal efficiency can be enhanced. On the other hand, there are various issues such as the corrosion of fuel system parts, the deterioration of rubber and resin materials, and the reduction in fuel economy due to the lower heating value. Also, there are issues with low temperature starting and drivability because of the lower vapor pressure.

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Table 1 Fuel properties

	E0	E100
Heating value (MJ/Air kg)	2.95	2.99
Octane number RON/MON	93/81	110/92
Stoichiometric air fuel ratio	14.6	9.0
Latent heat of evaporation (kJ/Air kg)	30.2	101
Boiling point (°C)	25-200	78
Theoretical air fuel ratio (Volume after carburetion)	43.1	14.3
Ratio of the number of moles of combustion before and after	1.07	1.14

Table 2 Engine specifications

	2006 Gasoline engine	2007 FFV engine
Fuel	E20-E25	E20-E100
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	81 × 87.3	81 × 87.3
Displacement (cm ³)	1799	1799
Compression ratio	10.5 : 1	11.5 : 1
Valve train	SOHC i-VTEC Inlet delayed closure	SOHC i-VTEC 1 intake valve inactive
Number of valves	4 per cylinder	4 per cylinder
Valve diameter (mm)	In.	32
	Ex.	26

4. Engine Overview and Main Specifications

4.1. Engine

Figure 1 shows the appearance of the R18A FFV engine. Table 2 shows the major specifications of this engine in comparison with the gasoline engine it was based upon. Various enhancements were made with respect to the 2006 model of the gasoline engine, including the following:

- (1) A higher compression ratio suited to the fuel properties was applied.
- (2) To ensure low temperature starting, sub fuel injection devices were added on the intake manifold, and the intake manifold material was changed to aluminum.
- (3) To enhance low temperature drivability, the valve timing was changed.
- (4) To prevent valve recession when using ethanol, the valve and valve seat materials were modified.

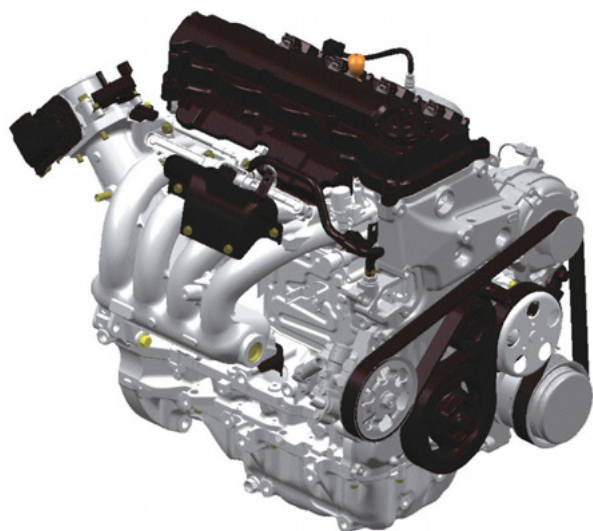


Fig. 1 R18A FFV engine

4.2. Fuel Supply System

Figure 2 shows the layout of the FFV fuel tank and fuel supply system. The fuel supply to the engine consists of the main fuel system, which supplies fuel from the main fuel tank, and the sub fuel system, which supplies fuel from the sub fuel tank. Figure 3 shows the main fuel

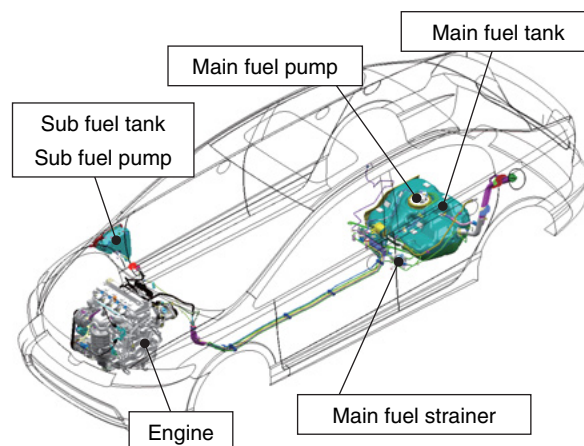


Fig. 2 Overview of CIVIC FFV fuel supply system

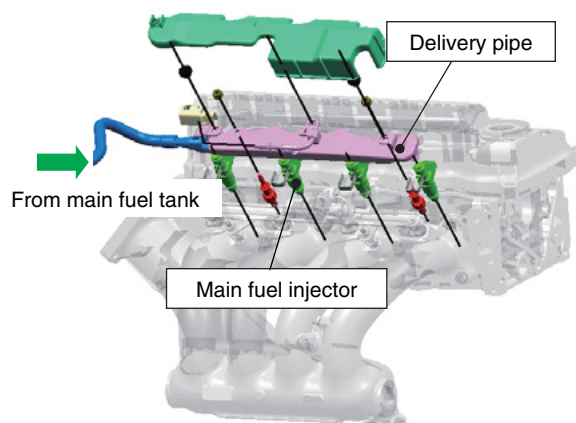


Fig. 3 Main fuel supply system

supply system. The delivery pipe material was changed to SUS 304 to enhance its resistance to corrosion by ethanol. This delivery pipe and the FFV main injector shown in Fig. 4 construct the system. Figure 5 shows the sub fuel system, which consists of the sub delivery pipe, sub fuel injector, and solenoid valve installed to assist with low temperature starting.

The fuel tank was adapted from the tank developed for the 2006 model gasoline vehicles. A fuel pump module specifically for use with E 100 was added. Although the conventional fuel strainer was integrated into the fuel pump module, it was changed to an external strainer at the fuel tank for easier maintenance and replacement.

An auxiliary fuel tank (hereafter referred to as the sub tank) for use in starting the engine is located under the right front fender. The sub tank fuel fill door was placed in the right fender to enhance product appeal when refueling. It is harder to start the engine at low temperatures when using E 100 or high-concentration ethanol as fuel. Therefore, the gasohol in the sub tank is supplied to the engine during startup to assist the startup process. The fuel in the sub tank is only used when

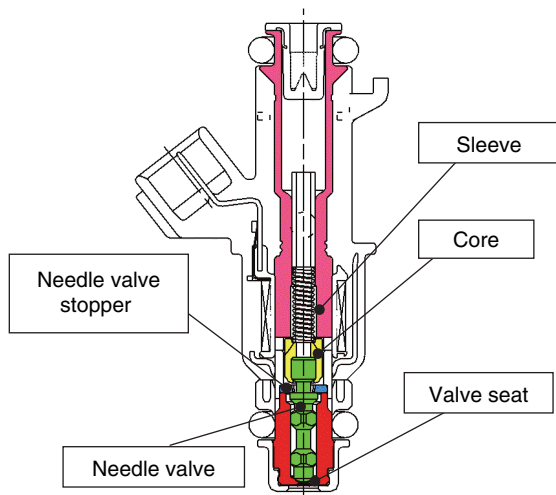


Fig. 4 Fuel injector for FFV

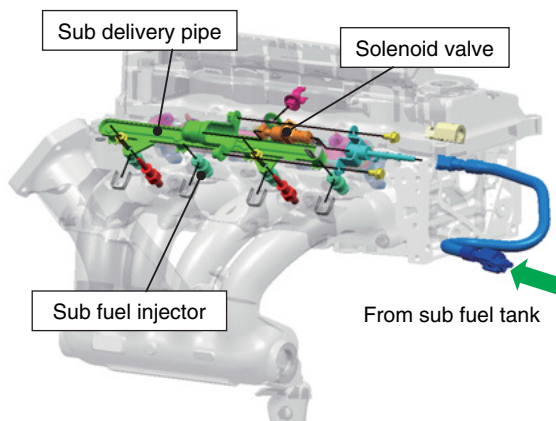


Fig. 5 Sub fuel supply system

Table 3 Material for main fuel system

Parts		Gasoline engine	FFV engine
Fuel injector	Valve seat	SUS440C	ATS34 Passivation film
	Needle valve	SUS440C	ATS34 Passivation film
	Needle valve stopper	SUS440C	SUS440C Passivation film
	Core	PB	K-M62F Passivation film
	Sleeve	K-M35FL	K-M62F
Delivery pipe		JSH270C Electroless Ni-P plating	SUS304L

starting the engine at low temperatures. The sub tank was made with a capacity of 700 cm³, a size that was chosen after taking into account the rate of fuel consumption and the frequency of refueling. The fuel pump module in the sub tank was adapted from modules used in gasoline vehicles.

4.2.1. Main fuel supply system

The main fuel system has highly concentrated ethanol or E 100 supplied from the main fuel tank. Materials with enhanced corrosion and wear resistance were adopted for use in the delivery pipe and injectors.

As shown in Fig. 3, fuel from the main fuel tank is supplied to each cylinder through the delivery pipe and injectors. The material for the delivery pipe was changed to SUS 304, which enhances its resistance to corrosion from ethanol.

Figure 4 shows the structure of the main injector. These differ from the injectors for use with gasoline in that different materials were used in each part and efforts were made to enhance resistance to corrosion and wear. Table 3 presents a comparison of materials used for the main injectors and delivery pipe in this engine and in a gasoline engine.

4.2.2. Sub fuel supply system

Low temperature starting performance declines when using highly concentrated ethanol. Therefore, gasohol is supplied from the sub tank to assist during engine startup.

Figure 5 shows the sub fuel system used for starting that is attached to the intake manifold. Figure 6 shows the cross-section of a sub fuel injector installed on the intake manifold. The system consists of the sub fuel injectors, the sub delivery pipe, and the solenoid valve installed on the aluminum intake manifold. Gasohol is supplied from the sub fuel tank when the engine is using high concentrations of ethanol and is doing a low-temperature start. The sub delivery pipe is filled up with

gasohol through the solenoid valve, and the sub fuel injectors installed in each cylinder supply the fuel to the cylinders. The mechanism is configured so that when it determines that the engine has started, it will stop the supply of fuel from the sub tank and close the solenoid valve, thus cutting that fuel off.

When the engine is starting in a warm condition or the fuel in the main fuel tank is gasohol, the engine can be started with the main supply of fuel alone. When this is the case, the sub fuel is not supplied to the engine.

4.3. Output characteristics

4.3.1. Characteristics during combustion of ethanol

A comparison of gasoline with ethanol, when used as an internal combustion engine fuel, is shown in Table 1.

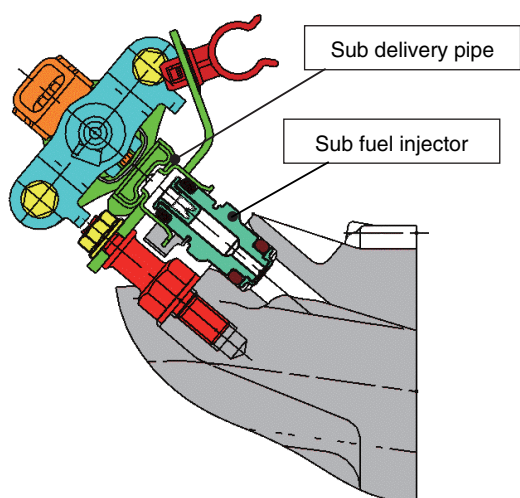


Fig. 6 Side view of sub fuel injector

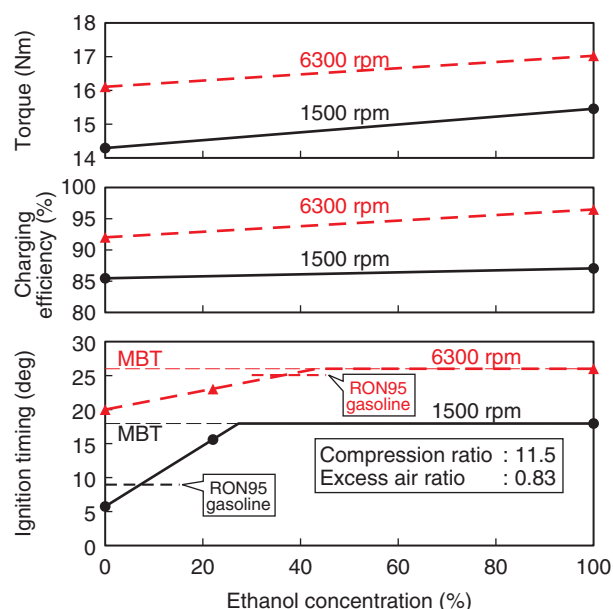


Fig. 7 Relation of ethanol concentration to ignition timing, charging efficiency and engine torque

Figure 7 shows the relationship of ethanol concentration to the setting of ignition timing, charging efficiency, and engine torque. Test results confirmed the following points:

- (1) There is virtually no difference in the MBT at wide open throttle.
- (2) RON enhancement makes it possible to advance the ignition timing (effect is greater at low speeds).
- (3) The increase in latent heat evaporation yields an increase in charging efficiency (effect is greater at high speeds)
- (4) Greater power is achieved by advancing the ignition timing and enhancing charging efficiency (effect is greater at low speeds).

It was confirmed that increasing the concentration of ethanol raises the RON and makes it possible to advance the ignition timing. E 22 has the lowest RON in the Brazilian market, and it can be inferred to have a RON higher than RON 95 gasoline at low speeds. At high speeds, however, it can be inferred to have a lower RON than RON 95 gasoline. The enhancement in charging efficiency from latent heat evaporation is thought to have a greater effect at higher speeds, where the volume of fuel injected per unit of time is greater.

Figure 8 shows the relationship between ethanol and gasoline under the same conditions for cylinder pressure and temperature in the high speed range. Even though cylinder pressure rises, the increase in the number of moles following combustion results in a decrease in cylinder temperature. Table 4 shows the comparison of output power, maximum cylinder pressure, and maximum cylinder temperature between ethanol and gasoline operations. The power is approximately 4% greater, but the maximum cylinder temperature is lower.

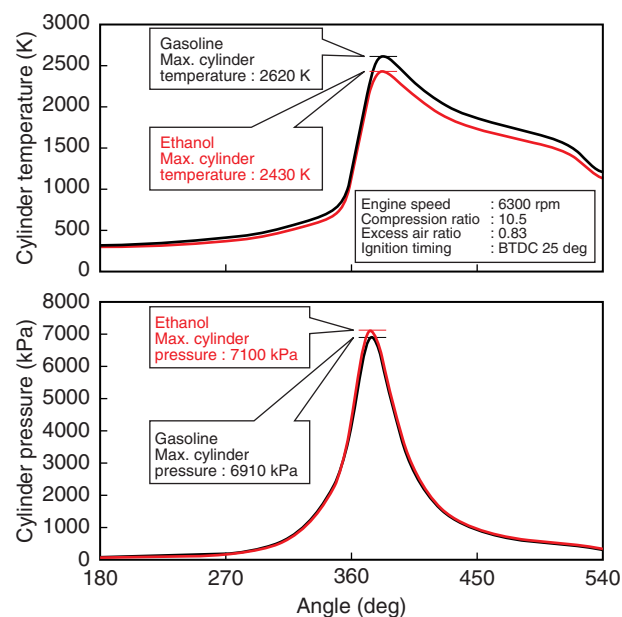


Fig. 8 Comparison of cylinder pressure and temperature for ethanol and gasoline

Table 4 Comparison of engine power for ethanol and gasoline

	Ethanol	Gasoline
Output power (kW)	107.6	103.6
Max. cylinder pressure (kPa)	7100	6910
Max. cylinder temperature (K)	2430	2620

Table 5 Engine power

	Ethanol	Ethanol 22% Gasoline 78%
Max. power (kW/rpm)	103/6200	102/6200
Max. torque (Nm/rpm)	174/4300	172/5000

4.3.2. Engine performance at wide open throttle

The characteristics of this engine are as follows:

- (1) Greater charging efficiency in the low speed range, as well as higher flow velocity, yielding operation on a single intake valve with enhanced brake specific fuel consumption (BSFC) under conditions of low water temperature combustion and partial load
- (2) High power output operation on two intake valves in the high speed range
- (3) A compression ratio that takes into account vaporizability when using 100% ethanol and knocking properties at the lower limit of ethanol concentration

Figure 9 and Table 5 show the engine output at upper and lower limits of the ethanol concentration.

4.4. Engine Performance at Low Water Temperature

4.4.1. Characteristics of ethanol at low temperatures

Issues associated with use of ethanol as motor vehicle fuel include low saturated vapor pressure at low temperatures resulting in poorer startability. Gasoline contains components with low boiling points, such as butane, that provide adequate vapor pressure even at low temperatures. With ethanol, the vapor pressure needed for combustion at low temperatures can not be attained. Increasing the amount of injection is ineffective because ethanol does not contain other components with low

boiling points such as in gasoline. It is important to take these characteristics of ethanol into account and select specifications that are suited to the FFV.

The basic specifications that are suited to the FFV were examined. With charging efficiency taken into account, the pressure and temperature after compression can be shown as follows:

$$P_C = P_0 (\eta_v \varepsilon)^\kappa \quad (1)$$

$$T_C = T_0 (\eta_v \varepsilon)^\kappa \quad (2)$$

P_C : Cylinder pressure after compression

P_0 : Intake manifold pressure

T_C : Cylinder temperature after compression

T_0 : Intake air temperature

η_v : Charging efficiency

ε : Compression ratio

κ : Specific heat ratio

The saturated vapor pressure rises sharply relative to temperature, with these results:

- (1) Increased charging efficiency (low speeds)
- (2) Higher compression ratio

These raise the cylinder temperature, increasing the vaporizability of the ethanol under low ambient temperature conditions. Putting one intake valve at rest is also an effective method of raising the flow velocity of the air-fuel mixture and increasing the vaporizability of ethanol, because of increasing contact by the ethanol with the intake air and cylinder wall.

The compression ratio for this engine was determined to accommodate different ethanol contents ranging from 20 to 100%. A VTEC mechanism was adopted to operate the valve timing, which determines charging efficiency, so that the system could switch back and forth between:

- (1) Operation with one intake valve, for starting the engine and for low speeds
- (2) Operation with two intake valves, for high speeds

This has achieved both driveability and adequate top power output.

4.4.2. Combustion characteristics of ethanol at low temperatures

The second issue arising from the use of ethanol as motor vehicle fuel includes starting the engine at low ambient temperatures and high-load operation (acceleration), when making a standing start immediately after startup. Figure 10 shows the air-fuel ratio

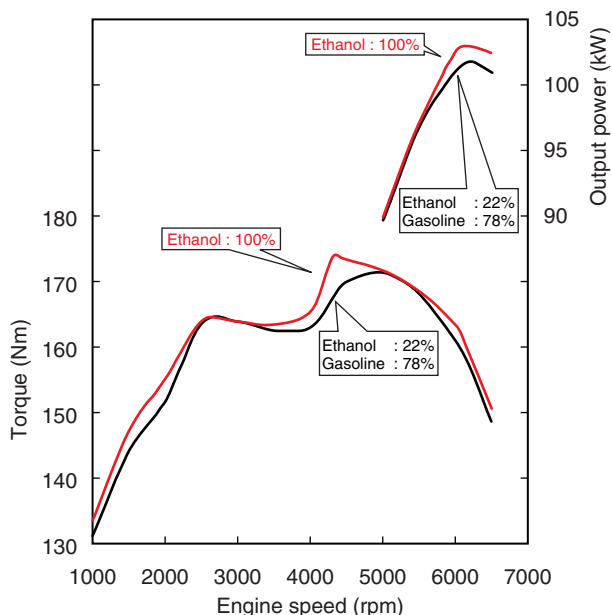


Fig. 9 Engine performance

Table 6 Comparison of MBT after cold start and after warm-up

Intake pressure (kPa)	MBT BTDC (deg)	
	Tw=80°C Ta=25°C	Tw=-10°C Ta=-10°C
-60	25	30
-13.3	10	25

characteristics with low intake air temperatures and low water temperature. The intake pressure of -60 kPa represents the idling state immediately after startup, while the intake pressure of -13 kPa represents the high-load state when starting. In high-load operation using ethanol, the total hydrocarbon concentration (THC) is high. This is thought to be because the intake air temperature and water temperature are low, so that the large amounts of ethanol involved in high-load operation cannot be vaporized. Ordinarily, the concentration of CO₂ is at a maximum with the theoretical air-fuel ratio. Ethanol that is not vaporized is not involved in combustion, however, so that λ reaches its maximum at around 0.9. Table 6 shows the relationship of MBT to intake pressure, water temperature, and intake air temperature. The MBT varied with the load, and the timing was advanced farther under higher loads. The reason is that high loads involve the injection of large amounts of fuel, and the resulting lower vaporizability means that ignition should be advanced in order to obtain good combustion.

4.4.3. Transient combustion characteristics

One of the challenging conditions for driving with

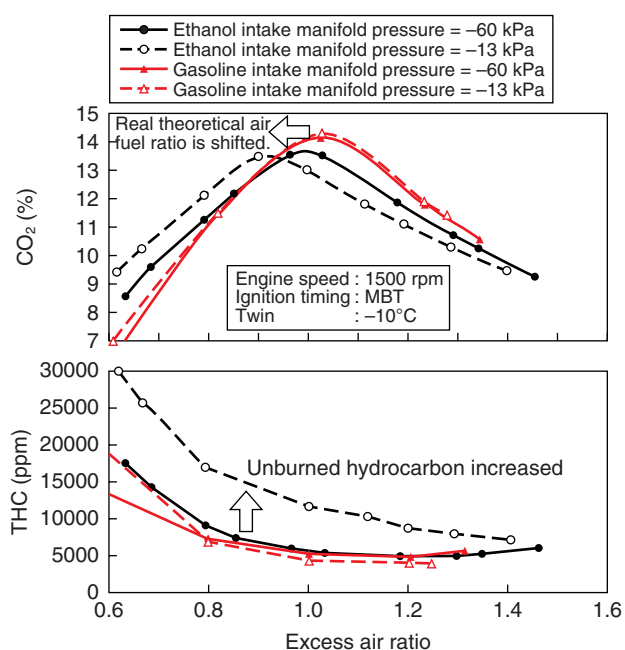


Fig. 10 Characteristics of excess air ratio at low temperature

ethanol as the fuel is when high-load operation follows immediately after engine start. The torque was measured at the transition to high-load operation to serve as an index for evaluation. Figure 11 shows the torque characteristics during the transition when partial load, immediately after startup, is suddenly changed to high-load operation. Figure 12 shows the torque characteristics of the steady state in the case of high-load operation immediately after the engine is started. When operating with two intake valves, misfires take place under high-load operation, even with a cooling water temperature up to 13 °C.

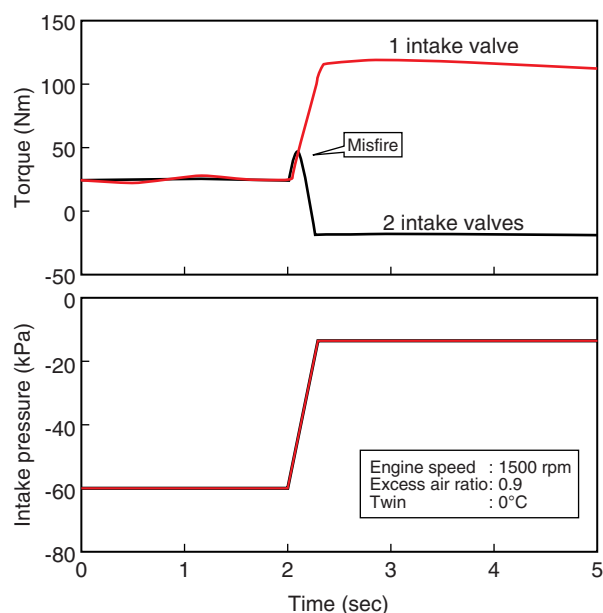


Fig. 11 Comparison of torque during acceleration between 1 intake valve and 2 intake valves

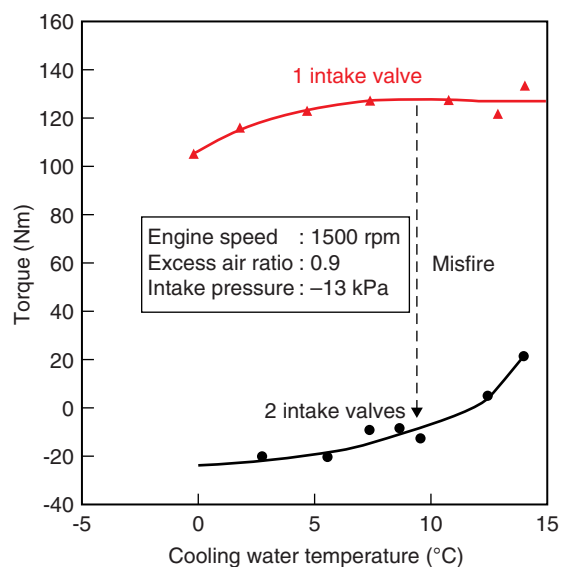


Fig. 12 Comparison of torque during acceleration between 1 intake valve and 2 intake valves

When driving with one intake valve, good combustion can be obtained, even with a cooling water temperature of 0 °C, which corresponds to the condition immediately after startup with the lowest ambient temperature experienced in Brazil. The reason is thought to be that the increased flow velocity and the generation of swirls increase the contact frequency of fuel, intake air, and cylinder wall. This then enhances vaporization.

5. Fuel Control

5.1. Main Fuel Control

The fuel control specifications were modified for the FFV according to the fuel properties as they differ from the properties of fuel used in a gasoline engine.

5.1.1. Ethanol concentration learning

As in the case of the gasoline engine, this engine uses a Universal Exhaust Gas Oxygen sensor (hereafter UEGO sensor) to operate with stoichiometric feedback (hereafter F/B). Ethanol and gasohol, however, have different theoretical air-fuel ratios, so that greater amounts of fuel are required when ethanol is used than when gasohol is used. The increase in the amount of required fuel is detected by the UEGO sensor, and the system then estimates the ethanol concentration of the fuel in the main tank.

The supply of fuel sometimes involves the supply of fuel that is different from the fuel presently in use. This means that the output of the fuel level sensor in the fuel tank is used to determine when fueling takes place. At that time, the system relearns the ethanol concentration.

5.1.2. Fuel compensation for ethanol concentration

Ethanol has a higher boiling point and lower vapor pressure than gasohol, and therefore does not vaporize as readily at low temperatures. Consequently, combustion at low water temperature requires a larger amount of fuel than is accounted for just by the difference between the theoretical air-fuel ratio of ethanol and that of gasohol. The system therefore selects a fuel volume increase factor for start-up that corresponds to the ethanol concentration learning value, and implements a wall-wetting fuel compensation control according to the ethanol concentration.

5.1.3. A/F F/B factor active limits

Virtually the only factor that influences the output of the UEGO sensor during stoichiometric operation of a gasoline engine is variation in the precision of the component parts. There is no need to set a wide margin for F/B. In addition, the FFV conducts stoichiometric F/B using fuels with a wide variation in their theoretical air-fuel ratio, so the F/B margin has to be set wide. However, simply setting a wide spread between upper and lower F/B limits of the gasoline vehicle may promote unnecessary

Table 7 Emission standard

Stage	CO	NMHC	(g/km)
			NOx
PROCONVE L-4	2.0	0.16	0.25
PROCONVE L-5	2.0	0.05	0.12

fuel F/B. Consequently, the initial values for the upper and lower limits are set as for a gasoline vehicle, and the system configured so that when the F/B factor reaches the limit value, it judges that a different fuel is now being used, and gradually widens the limits. This achieves a combination of both positive fuel F/B performance and fuel switchover learning performance.

5.2. Sub Fuel Control

When the ambient temperature is low and a high concentration of ethanol is being used, the startup time can be prolonged or startup may not occur. As a result, when the water temperature at startup does not rise above a set temperature and the ethanol concentration is above a set value, the sub fuel from the sub tank is injected into the inlet port to assist in engine startup. The system is configured to implement control in that manner, and thus provides good starting performance across a wide range of temperatures, regardless of the fuel being used.

6. Brazilian Exhaust Gas Regulations and Low Emission Technology

6.1. Brazilian Exhaust Gas Regulations

Table 7 shows the PROCONVE L-4 regulations that were implemented starting on January 1, 2005. It also shows the PROCONVE L-5 regulations, which are slated to be adopted from 2009, for reference. This engine complies with PROCONVE L-4. A distinctive requirement of legal statutes in Brazil is that they mandate satisfaction of the above regulation values for the three types of test fuel shown below.

- (1) AEHC (hydrated ethyl alcohol fuel)
- (2) E-22 gasoline (a mixture of 78% standard gasoline and 22% anhydrous ethanol) (v/v)
- (3) A compound of 50% standard E-22 gasoline and 50% standard AECH (v/v)

The FFV is capable of using any mixture of fuel. That is why this legal requirement was established.

6.2. Exhaust Gas Treatment System

Figure 13 shows the results achieved in meeting emissions requirements. An EGR valve was removed from the exhaust system for the base gasoline vehicle. Items (1)-(3) in the figure show the various test fuels mentioned above. When the concentration of ethanol is higher, larger amounts of fuel, relative to gasoline, are required when starting and immediately after starting the engine. This is why the volume of NMHC emissions tends to grow larger.

7. Afterword

The FFV engine developed in this project was mounted in the CIVIC to be sold in Brazil. Equipped with VTEC and sophisticated fuel control, the vehicle achieves both compatibility with diverse fuels and superior emission performance. The development goals that were initially set for the project have been met.

This development project has established basic technology for satisfying emissions controls, which will be made more stringent in the future, as well as for ethanol fuel mixtures, which are being adopted worldwide at an increasingly rapid pace. Additional enhancements will be incorporated in the future with the goal of developing a highly efficient power train that is capable of satisfying the demands of different regions and different times.

References

- (1) Arai, S., Muraishi, T.: HONDA Compressed Natural Gas Vehicle, HONDA R&D Technical Review, Vol. 9, p. 17-24
- (2) Toda, T., Matsuki, M., Ohmori, T., Yamamoto, Y.: Development of a 1.7L CNG Engine for the 2001 Civic GX, Honda R&D Technical Review, Vol. 14, No. 1, p. 49-56
- (3) Nakajima, S., Goto, H., Watanabe, O., Matsunaga, T., Nakashima, H., Nakajima, M.: Development of 1.8L CNG Engine for 2006 Civic GX, Honda R&D Technical Review, Vol. 18, No. 2, p. 116-124
- (4) Seko, K., Taga, W., Torii, K., Nakamura, S., Akima, K., Sekiya, N.: Development of 1.8L i-VTEC Gasoline Engine for 2006 Model Year Honda CIVIC, Honda R&D Technical Review, Vol. 18, No. 1, p. 8-15

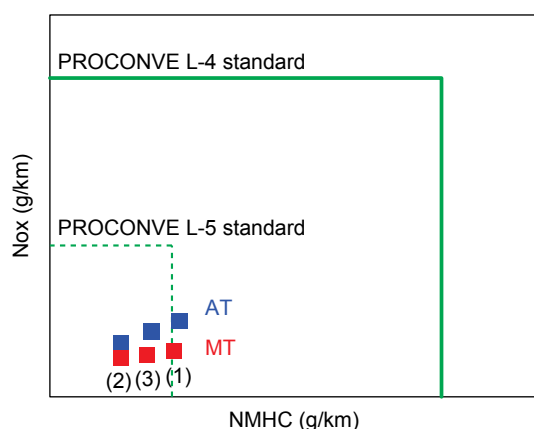
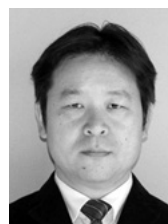


Fig. 13 Achievement of exhaust emission

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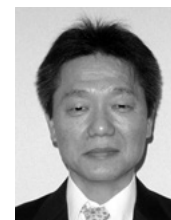
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