

Development of a New Power Train for the Civic Hybrid

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ABSTRACT

The Civic Hybrid was developed as a compact passenger hybrid car that achieves both low fuel consumption and cleaner operation from the viewpoints of preserving the global environment and conserving resources. The engine has lean-burn countermeasures added to the base i-DSI 4-cylinder 1.3-liter SOHC 2-ignition plugs/cylinder engine mounted in the “Fit”. In addition, the cylinder idling system has been adopted to increase the regenerated energy during deceleration. The hybrid system is based on the Honda IMA system, and the maximum regenerative torque has been increased by approximately 30% by improving the magnetic circuits of an ultra-thin DC brushless motor and adopting a new rotor manufacturing method. Fuel economy is improved by a new hybrid power train incorporating a CVT that further improves transmission efficiency, thus achieving the low fuel consumption of 29.5 km/l in the 10-15 mode. New emission technologies applied are a new exhaust system with a NO_x adsorption reduction type three way catalyst and air-fuel ratio control achieved 75% reduction from the 2000 emission standards in Japan. The power control unit, which is the IMA system control unit, was downsized and located behind the rear seat, thus ensuring comparable trunk capacity to the base vehicle of the Civic Ferio.

1. Introduction

The demand for low fuel consumption, low emission automobiles is growing ever stronger, due to the direction of preserving the global environment and conserving resources. For gasoline engines, in addition to lean-burn, there has been research into different types of engines, including direct injection and Miller cycle engines, and the creation of new products. At Honda, research and development has continued since 1992 into lean-burn engines⁽¹⁾⁻⁽⁵⁾ adopting technologies such as the VTEC device (VTEC: Variable Valve Timing and Lift Electronic Control).

The possibilities are great for hybrid systems, too, that combine electricity (motors) with engines. At Honda, an IMA (Integrated Motor Assist) system was developed as a hybrid technology. IMA entered the market in 1999 fitted to the ultra low fuel consumption vehicle “Insight”⁽⁶⁾.

Now a new IMA system, based on the previous IMA system, has been developed with improved motor torque and efficiency. A new 1.3 L lean-burn engine (LDA model) has been developed based on the L13A i-DSI (DSI: Dual and Sequential Ignition) engine⁽⁷⁾ installed in the “Fit” with an added cylinder idling system. These were installed in the “Civic”. This paper introduces the new IMA system and the engine technology.

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2. Aims of Development

Honda's first hybrid vehicle, the "Insight," achieved the lowest fuel consumption for mass production passenger vehicles worldwide, demonstrating the potential of hybrid technology. Now, based on the hybrid technology fostered with the Insight, the development aim was a 5-passenger, compact sedan hybrid vehicle that realizes "low fuel consumption and environmental measures." The engine was modified on the foundation of a compact hybrid power train design that corresponds to the vehicle package, achieving low fuel consumption through higher efficiency of the DC motor and CVT. In addition, adopting a lean NOx catalyst and modifying the exhaust system achieved lower emissions.

The concrete development targets are as follows.

- (1) No. 1 in fuel economy, in the 5-passenger compact sedan class
- (2) Low emission performance
Japanese J-ULEV "Ultra Low Emissions" certification
USA ULEV: Ultra Low Emission Vehicle
- (3) A compact IMA design that can be fitted in the Civic to maintain trunk space capacity
- (4) Highly responsive performance in the normal range

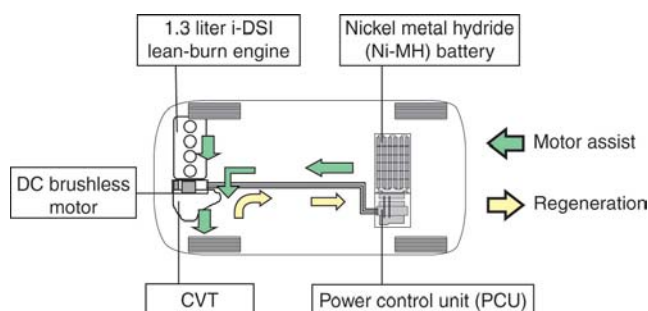


Fig. 1 IMA system construction

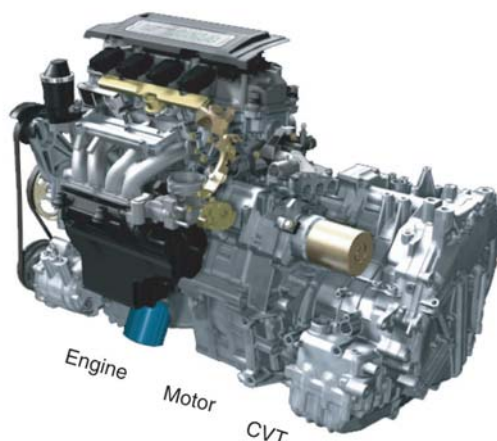


Fig. 2 View of IMA power train

3. Hybrid Systems and Low Fuel Consumption Technology

As a hybrid system, a simple, lightweight, compact IMA system was adopted. As shown in Fig. 1, the IMA system construction has a DC brushless motor between the engine and transmission and has a nickel metal hydride battery and power control unit (PCU) at the rear of the vehicle. It is a parallel hybrid power train that uses the engine as the major power source. The motor is used as a supplementary power source during acceleration, while during deceleration regenerative braking only is used. The engine is based on the i-DSI (L13A model) having output characteristics that satisfy, in combination with the motor, drive performance required of a Civic. Fig. 2 shows a view of the power train.

Development focused on increasing regenerated energy, making each system more efficient and lighter. In addition, efforts were made to improve the transmission efficiency. Against the base vehicle Civic iE⁽⁵⁾ (10-15 mode fuel consumption rate of 20 km/L), the ratio of contribution of each system towards lower fuel consumption is as shown in Fig. 3.

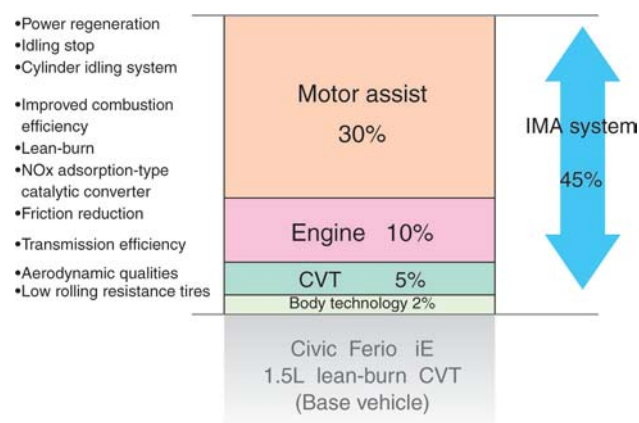


Fig. 3 Ratio of contribution to improve 10-15 mode fuel economy

Table 1 Engine specifications

Engine code		LDA
Cylinder configuration		In-line 4-cylinder
Bore × stroke (mm)		73 × 80
Displacement (cm ³)		1 339
Compression ratio		10.8 : 1
Valve train		SOHC Cylinder Idling System (CIS)
Number of valves		2 per cylinder
Valve diameter (mm)	Inlet	32
	Exhaust	28
Ignition system		Dual and Sequential Ignition (DSI)
Exhaust manifold		Stainless steel
Catalytic converter		Under floor 2 bed Front: TWC Rear: Lean NOx
Max. power (kW/rpm)	Without	63 / 5 700
Max. torque (N-m/rpm)	Motor assist	119 / 3 300

4. Engine

4.1. Engine General Specifications

Table 1 gives the engine's general specifications. The fundamental spec is based on the i-DSI 4-cylinder, 1.3 liter SOHC 2-plug engine installed in the Fit, with additional IMA system modifications and measures to fit it to the Civic body.

In addition, the valve train adopted a cylinder idling system (CIS) to increase the regenerated energy during deceleration. Details are outlined below.

4.2. Output Characteristics

Decreasing engine capacity is effective in reducing fuel consumption, but is a problem when also trying to maintain vehicle dynamic performance. The output of the 1.3 L engine plus the motor is an output roughly equivalent to that of the D15B model 1.5 L VTEC-E engine (maximum output 77 kW, maximum torque 139 N·m) fitted to the base Civic iE. It is notable that the motor characteristics give high torque in the low speed range, providing a 20% improvement over the iE at 2,000 rpm torque (Fig. 4).

4.3. Cylinder Idling System (CIS)

4.3.1. Aims of CIS

Engine friction can be roughly divided into mechanical loss and pumping loss. The CIS developed in this project is a system that pauses inlet and exhaust valves in three cylinders during deceleration fuel cut. This reduces pumping loss and allows the friction energy to be stored through the motor as regenerated energy. Accompanying the increase in regenerated energy, there is an increase in the amount of motor assistance during acceleration, and as a result, fuel consumption is lower. Fig. 5 shows the engine friction during deceleration (throttle fully closed). Pumping loss is reduced by approximately 50% by CIS.

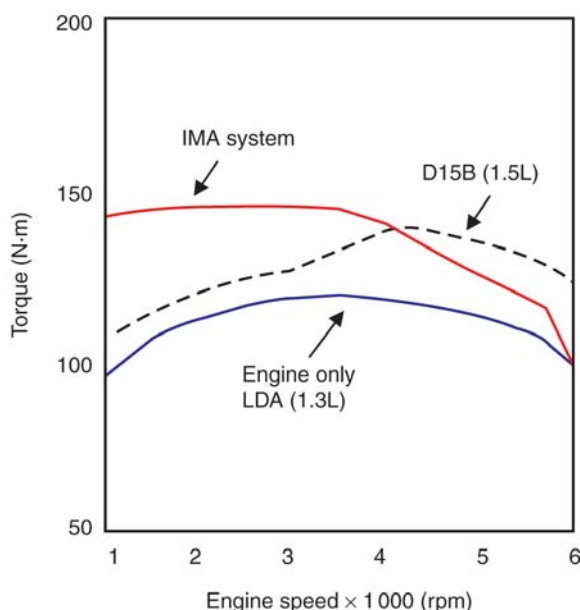


Fig. 4 Output performance of IMA system

Pumping loss would be almost zero when all valves in all four cylinders are paused. This would be effective in increasing regenerated energy. However, in order to maintain driver performance if there were a failure of CIS system parts, it was decided to apply the CIS mechanism for three cylinders.

4.3.2. CIS configuration

Fig. 6 shows the CIS hardware configuration. In the same way as with a conventional VTEC, it is a system hydraulically controlling the spool valve and pistons in the rocker arm, switching between inlet and exhaust valve lift and complete stop. This CIS rocker arm is used in cylinders No. 2 through No. 4. The No. 1 cylinder uses a rocker arm without a switching device.

Fig. 7 shows the CIS rocker arm construction. For one valve, construction is such that there are rocker arms A and B, pistons A and B, and a return spring. Conventional VTEC is a system that connects with hydraulic pressure and separates with spring reaction force. With the CIS, however, in order to maintain switching ability through the low rev range where hydraulic pressure is low (around 1,000 rpm), a hydraulic pressure to hydraulic pressure switching method is adopted to switch between connection and separation. Fig. 7-(c) shows a cross section of the rocker shaft. It is a 2-hole type adopted in the 3-stage VETC⁽²⁾.

A hydraulic pressure to hydraulic pressure switching method requires two hydraulic paths. The oil supplied from the main carrier switches between the valve-active side and the valve-inactive side paths, through the three-way type spool valve as shown in Fig. 8.

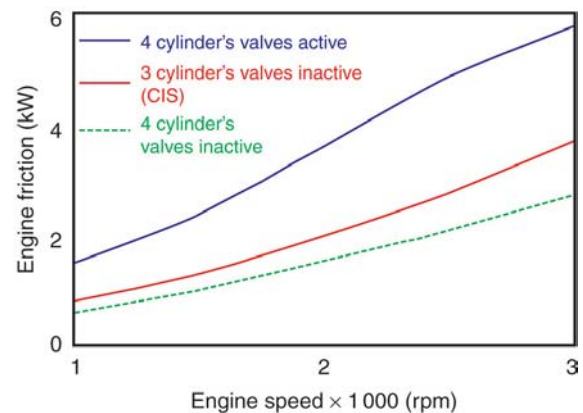


Fig. 5 Engine friction reduction effect by CIS

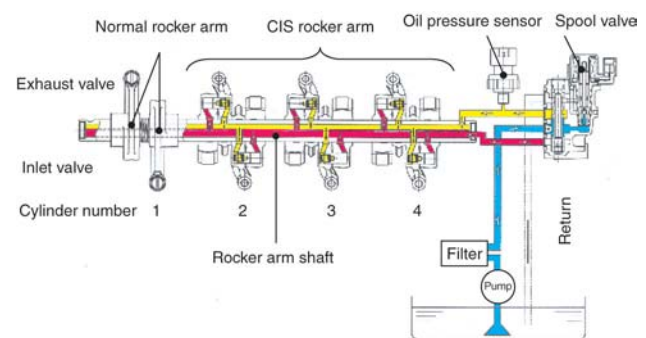


Fig. 6 CIS valve train and hydraulic passage

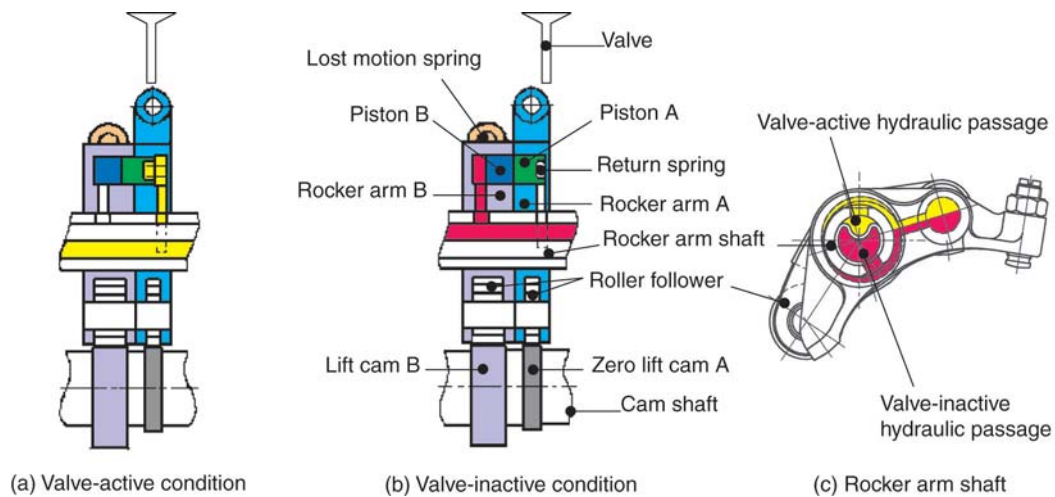


Fig. 7 CIS rocker arm and rocker arm shaft construction

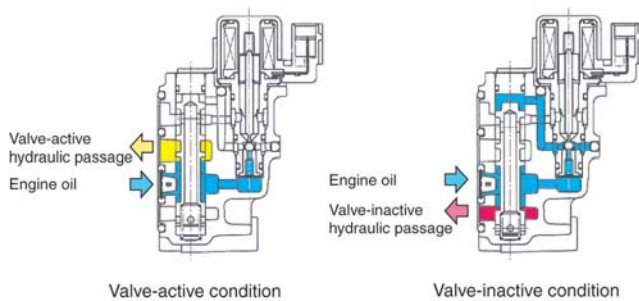


Fig. 8 Spool valve construction

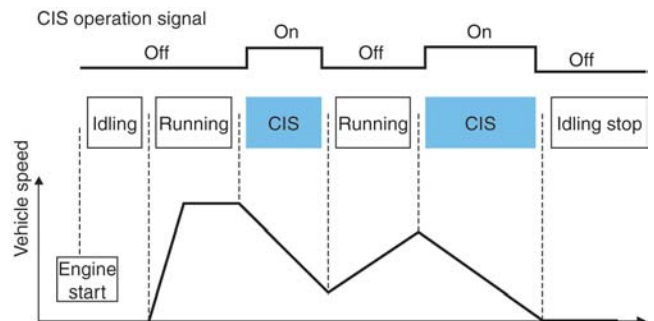


Fig. 9 CIS operation pattern during actual driving

The normal valve-active condition is shown in Fig. 7-(a). Hydraulic pressure is applied to rocker arm A, so rocker arm A and rocker arm B are connected by piston A. According to the profile of lift cam B, the connected rocker arms operate, and the valve is driven.

The valve-inactive condition is shown in Fig. 7-(b). With the spool valve switching, the hydraulic pressure is supplied to rocker arm B, and with the shifting of piston B, rocker arms A and B separate. Rocker arm A enters the valve-inactive state according to the profile of the zero-lift base circle cam A.

4.3.3. CIS operation range and control

The CIS is a system that increases regenerated energy by reducing engine friction during deceleration, and so works towards lower fuel consumption. It only runs under fuel injection cut conditions during deceleration, as shown in Fig. 9. Fig. 10 shows the system components. Under conditions of high oil temperature or low engine revs, hydraulic pressure drops. In order to improve CIS control accuracy with low hydraulic pressure, an oil pressure (Poil) sensor and oil temperature (Toil) sensor were adopted. CIS switching implementation is judged, combining information on engine revs and vehicle speed, high-pressure battery residual amount, etc. The motor regeneration amount is controlled according to the CIS operation state, and the deceleration feeling is the same as with an ordinary gasoline vehicle.

When the vehicle accelerates again after deceleration, the control system switches the spool valve over to the active side, starts operation of the intake and exhaust valve, then initiates fuel injection, in that order. This achieves smooth acceleration performance.

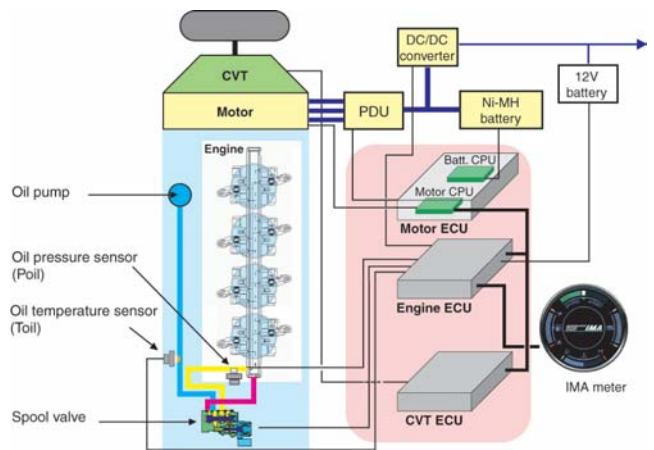


Fig. 10 CIS components

4.3.4. Cylinder pressure when valves are paused

Fig. 11 shows the maximum cylinder pressure when switching from valve operation to valve pause. The throttle is fully closed; No. 1 cylinder operates normally; and No. 2–No. 4 cylinders switch from valve operation to pause. The amount of air remaining in the cylinder differs according to the paused cylinders' inlet valve and exhaust valve pause timing. Cylinders that pause from the inlet valve immediately after the exhaust process (No. 4 cylinder in Fig. 11) have reciprocating action with TDC portion air capacity tightly closed. Cylinders that are paused from completion of inlet

process (No. 2 and No. 3 in Fig. 11) have reciprocating action with process portion air capacity tightly closed. According to valve pause switching timing, cylinder pressure immediately after switching differs according to the amount of air remaining in the cylinder, but at some dozens of cycles, cylinder pressure becomes saturated and equivalent.

The No. 1 cylinder, which is operating normally, has a rise in cylinder pressure, as inlet air amount increases in line with inlet pipe pressure rise due to the valves in the other three cylinders being paused.

4.4. Engine Friction Reduction

In addition to the low friction technologies adopted in the base engine L13A, plateau honing was adopted to smooth the cylinder sleeve surface roughness and to reduce piston sliding resistance (Table 2). Plateau honing is a machining method that forms oil pools to maintain the oil film, and at the same time improves surface smoothness. Fig. 12 compares surface states with conventional honing and plateau honing. Plateau honing achieves a reduction of 8% in mechanical friction at 1,500 rpm, and of 4% of friction, including pumping loss (inlet pipe pressure = -53 kPa).

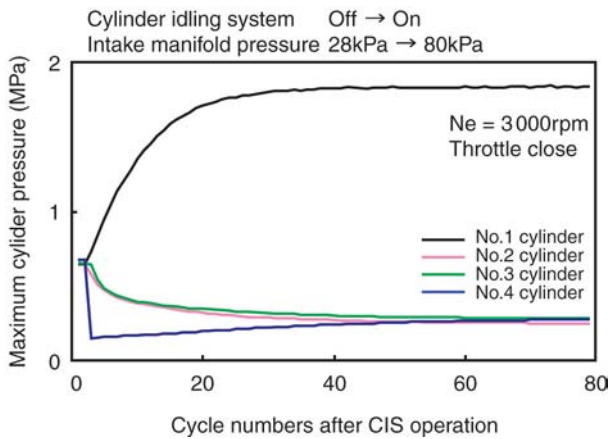


Fig. 11 Change in cylinder pressure patterns after CIS operation

Table 2 Engine friction reduction technology

○=Adoption

Engine code	LDA	L13A
Roller rocker arm	○	○
Off-set cylinder arrangement	○	○
Low tension piston ring	○	○
Streak crank bearing	○	○
MoS ₂ processing of piston skirt	○	○
Cam shaft chain drive system	○	○
Low-viscosity engine oil	○	○
Cylinder sleeve plateau honing	○	△
Two mode cooling system	○	○

4.5. Reduction in Fuel Consumption Rate

The combustion concept adopted by the L13A model i-DSI engine installed in the Fit is a rapid combustion concept using dual-point ignition⁽⁷⁾. A homogenous air-fuel mixture is formed through inlet port shape and combustion chamber shape, and together with dual-point ignition precision control, a high compression ratio was achieved. The LDA model specifications contributing to combustion are shared, but a lean-burn combustion method was adopted. Fig. 13 shows BSFC (brake specific fuel consumption) and co-variation of indicated mean effective pressure (IMEP) characteristics against air-fuel ratio. Against stoichiometric air-fuel ratio, through lean-burn a 10% BSFC reduction was achieved.

Honda adopted lean-burn combustion methods using VTEC-E for 4-valve engines. In the low rev range, one of the 2 inlet valves is almost completely paused (lift 0.5 mm), and due to high swirl (swirl ratio 2.5–3.4)⁽¹⁾⁻⁽⁶⁾, it is a stratified lean-burn combustion^{(5), (8)}. The i-DSI engine (swirl ratio 1.6) does not use this variable device, but rather actualizes homogenous lean-burn combustion through modified cylinder flow that includes a modified combustion chamber shape, and a dual-point ignition system. Fig. 14 shows the relationship between BSFC and engine displacement at 1,500 rpm, output power = 2.94 kW load. The LDA model achieved a BSFC level equivalent to the D15B that used the VTEC-E, and to the ECA1.

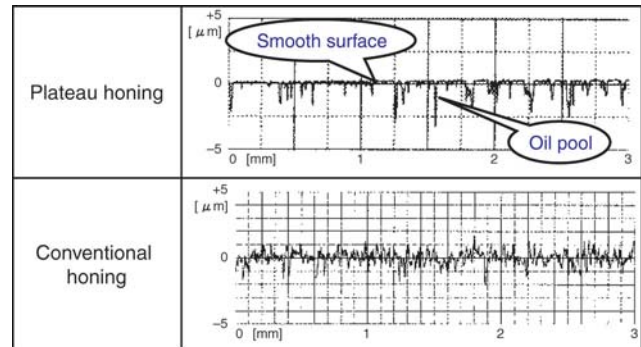


Fig. 12 Comparison of cylinder sleeve surface between plateau honing and conventional honing

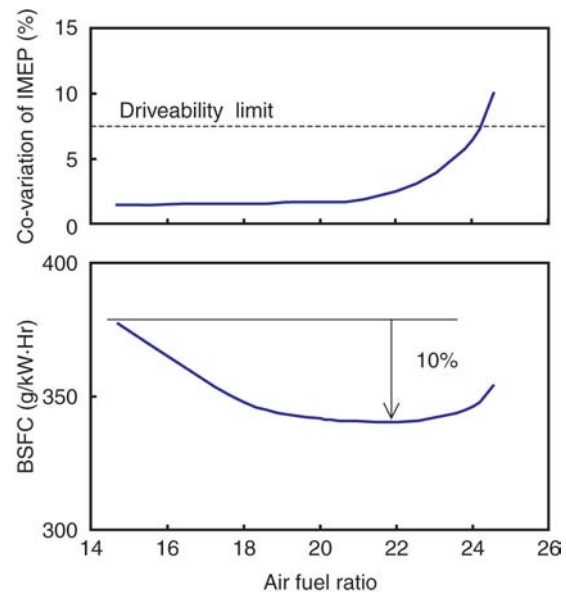


Fig. 13 Lean-burn effect on BSFC

Fig. 15 shows the simulation results of an engine in-cylinder air-fuel distribution with the LDA and the D15B. As for the calculation conditions, an average air-fuel ratio of $A/F = 22$ (excess air ratio = 1.5) was used, and fuel injection period and image crank angle (= ignition time) were actual engine driving conditions for both engines. The image surfaces were sections horizontal and vertical to the spark plug center electrode position. The LDA model has both vertical sections to the dual sparkplugs. In comparison with the D15B, the LDA forms a homogenous mixture.

5. CVT

5.1. Lightweight and Compact CVT

The transmission adopted was Honda's own Multi Matic S (CVT)^{(9), (10)}. This is a carryover of the basic framework of the transmission used in the Fit, made more compact. In comparison with the Civic iE, there is a reduction in total length of 5%, which makes it possible to fit the IMA motor in a Civic body. There is also a 5% reduction in weight, making it lightweight and compact. (Table 3)

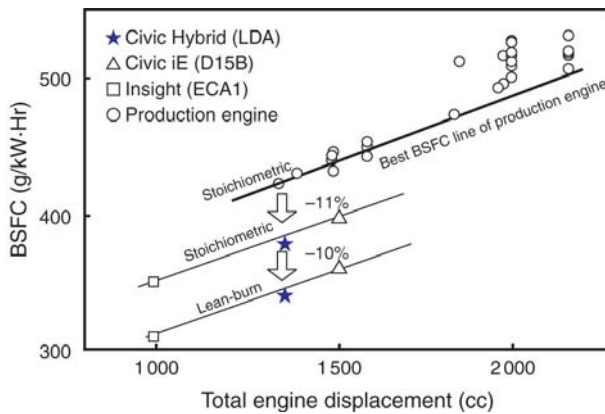


Fig. 14 Improvement of BSFC

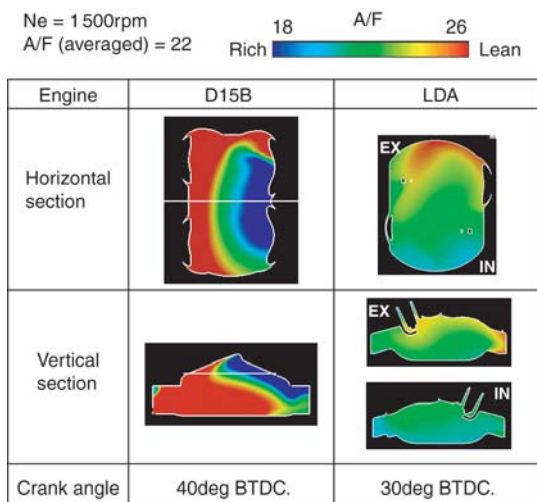


Fig. 15 Comparison of in-cylinder A/F distribution between LDA and D15B (VTEC-E)

5.2. CVT Low Fuel Consumption Technology

5.2.1. Friction reduction

Reducing pulley clamp hydraulic pressure through improved accuracy of engine torque estimates and a reduction in hydraulic pressure control variation has reduced friction by 20% over that used in the Civic iE. (Fig. 16)

5.2.2. CVT electronic control

In order to realize low fuel consumption, revisions were made to control system settings, making them even more accurate. The main items were as follows:

- Set optimum shift characteristics for low fuel consumption.
- Improved start clutch control method that achieves both high drivability and low fuel consumption.
- Refined start clutch feedback control during deceleration in order to increase regeneration amount.
- Increased accuracy of pulley clamp pressure.

Fig. 17 shows a characteristic comparison of pulley clamp hydraulic pressure command values during driving. By making the calculations of required hydraulic pressure more accurate, there is a reduction in hydraulic pressure command values. Through the above, a 5% reduction in fuel consumption was achieved, in comparison with conventional CVT control.

Table 3 CVT specifications

	Civic Hybrid	Civic iE
Belt axis length (mm)	143	155
Transmission length (mm)	352	372
Transmission weight [wet] (kg)	65.3	68.6

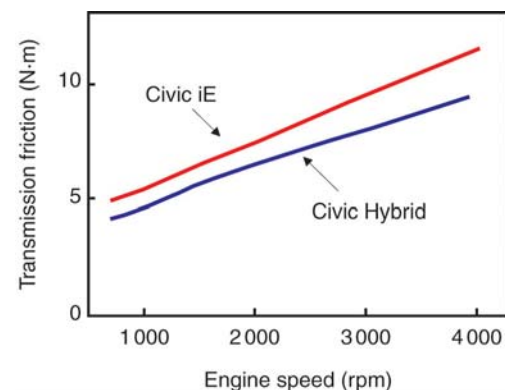


Fig. 16 CVT friction reduction effect

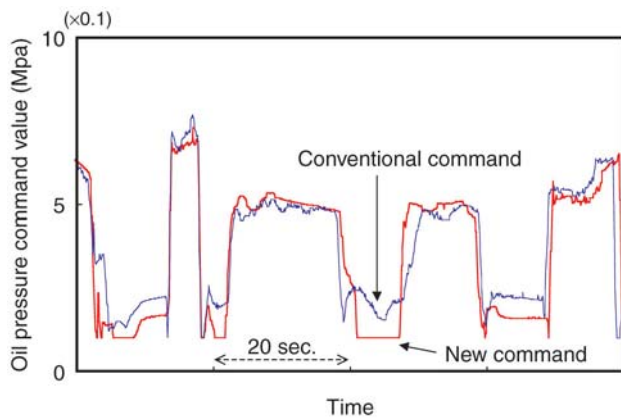


Fig. 17 Comparison of pulley clamp oil pressure command values

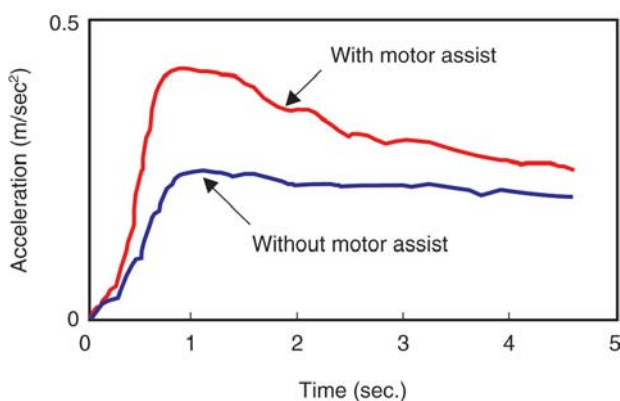


Fig. 18 Motor assist effect on vehicle starting performance

5.3. High Marketability through Combination with IMA

Fig. 18 shows start-off characteristics with and without motor assistance. Pending issues include an increase in vehicle weight due to installing the hybrid system, and a drop in acceleration performance due to smaller engine capacity. However, using motor assistance, it is possible to achieve 1.5 L class start-off performance without lowering the gear ratio.

In addition, by combining CVT and IMA, optimum prosmatec control is adopted, and even on mountain roads it is possible to achieve a high level of drivability.

6. New IMA, in the Pursuit of High Efficiency and Compact Size

To create a motor that responds to an increase in vehicle weight or an increase in regenerative energy, it is necessary to improve maximum regenerative torque and efficiency. The motor's external dimensions are equivalent to the Insight⁽⁶⁾, and it has improved performance with modifications to electromagnetic circuits.

Volume is reduced by making the electrical units, such as the power control unit (PCU) driving the motor, the battery, etc., centralized and compact; and by placing them behind the rear seats in a sedan type passenger vehicle, it is possible to maintain a practical trunk space.

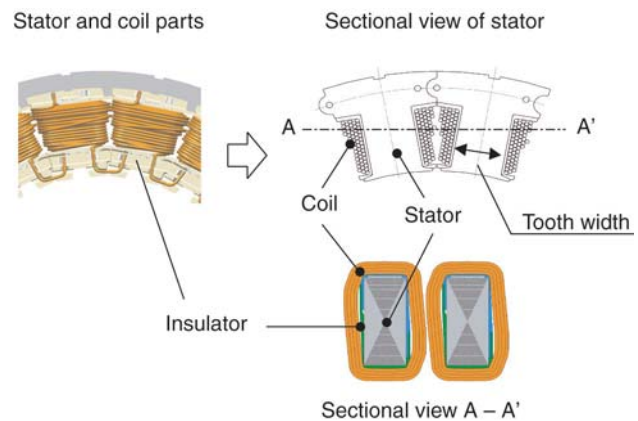


Fig. 19 Construction of stator and coil

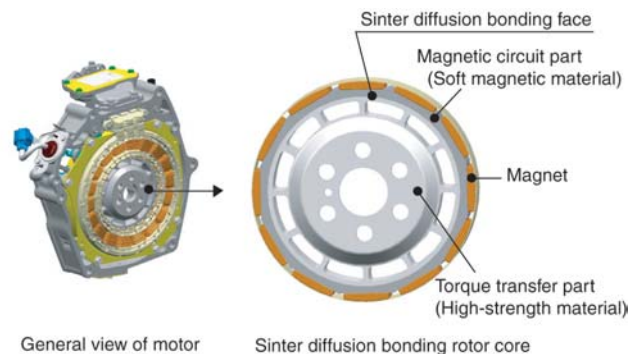


Fig. 20 Sinter diffusion bonding rotor core

6.1. Thin DC Brushless Motor

6.1.1. Motor performance improvements

As a means of improving motor performance with modifications to electromagnetic circuits, reductions in copper loss and iron loss, and improvements to torque constant (Nm/A) can be considered. Reductions in copper loss and iron loss can be made through measures expanding the diameter of the coil wire (+0.2 mm) and increasing the width of the teeth (+0.5 mm).

Winding the coil in the conventional method in the same space leads to contact between adjoining coils, and insulation performance cannot be maintained. As countermeasures, the insulator on the inner side of the coil was made thinner, and a shape adopted so that the thick part of the coils do not overlap at the center. The coil winding method was also modified. By adopting a non-symmetrical winding that effectively utilizes coil part space, a reduction in copper loss of approximately 30% was achieved, without changing the stator's external dimensions (Fig. 19).

There was an improvement of approximately 16% in torque constant, by expanding the magnetic circuit area (+5.5 mm) in the motor's axial direction. The space required for this is obtained by integrating functions of the parts inside the motor, keeping the external dimensions equivalent to those of the conventional unit.

Thanks to these improvements, the maximum regenerative torque was improved by approximately 30%, and efficiency in the normal range was improved by approximately 3%.

6.1.2. New rotor manufacturing method

A rotor must have the function of fixing magnets to the perimeter and creating electromagnetic circuits, and must

have the strength to transfer torque by being connected to the crankshaft. Conventionally, the rotor has been formed by applying the lost wax method, using carbon steel, giving priority to connection strength. In order to work towards both maintaining connection strength and at the same time improving motor efficiency, a high strength material was used on the inner side of the rotor, and a soft magnetic material on the outer side (Fig. 20). The rotor is formed by sinter diffusion bonding, which firmly bonds different metals. Through this, motor efficiency was improved, and weight reduced by 15% in comparison with the conventional unit.

6.2. Making Electrical Units Compact

Modifying the layout of the PCU controlling motor drive, the Ni-MH battery, and high pressure peripheral devices, as shown in Fig. 21, led to the creation of a compact electrical unit IPU (Intelligent Power Unit).

Modifications were also added to the IPU's cooling path. With the Insight, the PCU system and battery system had independent cooling paths, but with innovations in layout inside the IPU, a single path was realized. With these modifications, a compact shape was achieved, as well as a reduction of 42% in IPU volume, in comparison with the IPU fitted to the Insight.

As shown in Fig. 21-(b), the IPU is placed behind the rear seats, and trunk capacity is maintained that is no worse than gasoline based vehicles.

From the above, engine, transmission, and motor efficiencies are improved, achieving the target fuel consumption of 29.5 km/L in Japanese 10-15 mode.

7. Low Emission Technology

Conventionally, under the lean-burn condition, there is no expectation for NOx cleaning with a three-way catalyst, and so achieving low emissions is an issue.

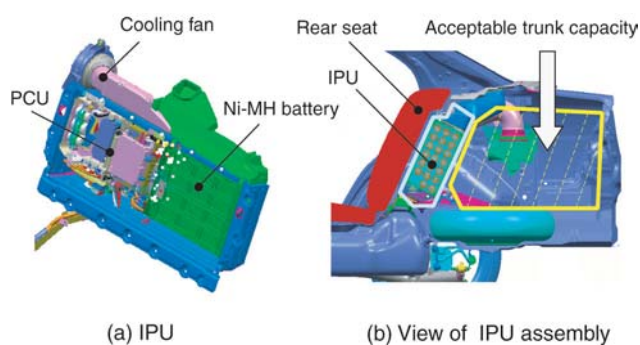


Fig. 21 View of IPU assembly



Fig. 22 View of exhaust system

In studying the emissions system for this engine, the target for domestic (Japanese) sales models was set at a 75% reduction from the 2000 emission standards in Japan (approval as "ultra-low emissions").

7.1. Exhaust System

The exhaust system for this engine is shown in Fig. 22. In order to maintain low emissions in the cold range and in stoichiometric air-fuel ratio range, a lightweight stainless steel exhaust manifold was adopted, reducing thermal capacity. Placing a 2-bed catalyst under the floor, in the front a 900 cell three-way catalyst was used, and in the rear a 600 cell NOx adsorption reaction three-way catalyst for lean burn⁽¹¹⁾ was used. By making the converter high density and thin walled, the catalyst's temperature rise characteristics are improved. By increasing the surface area in contact with the exhaust gases, there is improved emission conversion. A rolling type canning process was selected to achieve both high density and high contact surface area.⁽¹²⁾

7.2. Achieved Emission Values

In addition to the exhaust system, a multi-hole injector having a 6-hole nozzle and an electric EGR valve were adopted. Furthermore, the engine control systems outlined below were also adopted. This made possible an emission reduction level of 75% from the 2000 emission standard.

- STR (Self Tuning Regulator)⁽¹³⁾
- Quick Warm-up System⁽¹⁴⁾
- Lean control of air-fuel ratio for a low temperature start

In addition, in the North American spec, a 900-cell three-way catalytic converter was placed in the stainless steel closed-couple exhaust manifold integrated with the converter, and a 2-bed 400 cell three-way NOx adsorption reaction catalyst was placed under-floor. This meets the US ULEV, which is the global standard.

8. Summary

The following high fuel economy and emissions performances were achieved, thanks to the development of a new 1.3 L i-DSI lean burn engine of the LDA type adopting the cylinder idling system; the development of a new IMA system that improved motor efficiency by approximately 30%; and the development of a hybrid power train comprising a CVT with improved transmission efficiency.

- Japanese 10-15 mode fuel consumption rate 29.5 km/L
- A 75% reduction of the 2000 emission standards, gaining approval as "J-ULEV"

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