

Development of Low Emission Diesel Engine with DPF System

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ABSTRACT

Honda has developed a turbo-charged common rail diesel engine for the European version of its CR-V Sports Utility Vehicle (SUV). During this development measures have been implemented to address the issue of the SUV body having high running resistance. The promotion of homogeneity in the air-fuel mixture through the employment of a shallow dish combustion chamber and the reduction of the diameter of the fuel injection nozzle holes has enhanced combustion and reduced engine-out Particulate Matter (PM). In addition, the use of a highly efficient EGR cooler has increased the volume of EGR. Combined with the achievement of optimal EGR gas temperature control by means of an EGR cooler bypass system, these factors together have enabled the achievement of a reduction in NOx emissions.

The enhancement in exhaust emission performance resulting from these innovations has made the CR-V the first SUV which is compliant with the 2005 European diesel exhaust emissions standards (EURO-IV).

A diesel particulate filter (DPF) is also employed in the CR-V. Optimization of the multi-fuel injection system, which is able to inject up to four times per cycle, control of the DPF temperature via the use of a variable geometry turbocharger (VGT), and intake control by means of the throttle valve have all resulted in reliable DPF regeneration performance.

These various emission reduction technologies have resulted in the achievement of PM emissions less than one-tenth of those stipulated by EURO-IV.

1. Introduction

Concern for environmental issues is growing worldwide. Year by year the demand for diesel engines increases, as they provide both a means of reducing CO₂ emissions and high dynamic performance. On the other hand, emission regulations for diesel engines are becoming more stringent, and in some regions, there is

movement beyond the current regulations towards favorably treating vehicles fitted with diesel particulate filters (DPF) that can remove much particulate matter (PM). The demand for vehicles with DPF is rising steeply.

In 2003, Honda developed and introduced its first proprietary diesel engine for the Accord^{(1),(2)}, which has been well received in the market. Based on the diesel engine for the Accord, a new engine has been developed for the CR-V Sports Utility Vehicle (SUV)⁽³⁾.

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The CR-V is the first SUV that complies with the 2005 European diesel exhaust emissions standards (EURO IV) and at the same time achieves both high output and low fuel consumption. Combining this engine with the newly developed DPF system has made it possible to greatly reduce PM emissions. This paper reports on the engine technologies that comply with EURO-IV and on the DPF system.

2. Development Goals

In the development of this SUV engine, the following targets were set.

- (1) To be the first SUV to comply with EURO-IV.
- (2) To ensure top-level fuel economy and dynamic performance for an SUV diesel vehicle.
- (3) To create a DPF system (To reduce PM emissions).

3. System Outline

3.1. System Introduction

Figure 1 shows the i-CDTi engine system with DPF, as employed in the CR-V.

With the adoption of the DPF, throttle valves, exhaust temperature sensors, and pressure difference sensors were newly added, to enhance DPF regeneration performance.

Table 1 shows the main engine specifications. The fuel injection system is the BOSCH 2nd generation common rail system, which was also used in the Accord. In order to increase EGR gas, cooling performance of the EGR cooler was enhanced. In addition, an EGR cooler by-pass system was provided to reduce HC and CO gas emissions due to excessive cooling of the EGR gas at low water temperatures.

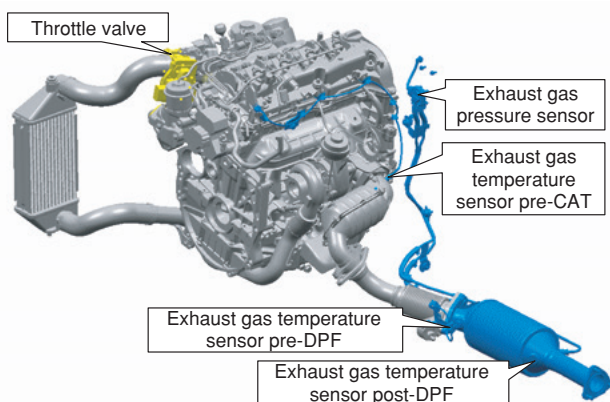


Fig. 1 Schematic diagram of i-CDTi engine with DPF system

Table 1 Main specifications of engine

Engine type	DOHC-4VLV
Displacement (cm ³)	2 204
Bore × Stroke (mm)	85 × 97.1
Compression ratio	16.7
Piston (Bowl diameter) (mm)	52.8
Bowl shape type	Shallow dish
Injector (mm)	φ 0.134 × 6holes
Fuel injection system	Common rail system
Maximum Power (kW/rpm)	103 / 4 000
Maximum Torque (Nm/rpm)	340 / 4 000
After treatment	DOC + DPF
EGR system	EGR cooler with bypass system

4. Engine Unit

4.1. Enhanced Combustion

With an SUV body having large running resistance, the amount of fuel that is injected increases with the increase in engine load. This expands the range where the local air-fuel ratio in the combustion chamber is small, and combustion worsens, leading to an increase in PM emissions. At the same time, the combustion temperature rises, leading to an increase in NO_x emissions. Accordingly, in working towards EURO-IV compliance, it is necessary to simultaneously reduce PM emissions through combustion enhancement, and to reduce NO_x emissions through advances in the EGR system^{(4), (5)}.

4.1.1. Reduction in PM emissions

PM emissions are thought to be caused by poor distribution of the mixture having a low local air-fuel ratio, and its expansion in the combustion chamber. Therefore, the following modifications were made, to homogenize the fuel spray and to distribute the spray near the bowl wall surface.

- (1) The diameter of the injector nozzle holes was reduced (micro-sac type 6-hole nozzle) to promote finer fuel spray particles.
- (2) The piston bowl diameter was expanded, and modified to a shallow dish, to promote wider distribution of fuel spray.

Figure 2 shows the results of a CFD simulation air-fuel mixture distribution analysis with the above injector specifications and combustion chamber shape changes. It is clear that reducing the diameter of the holes in injector nozzles promotes finer fuel spray particles, enabling homogenization of the mixture within the bowl.

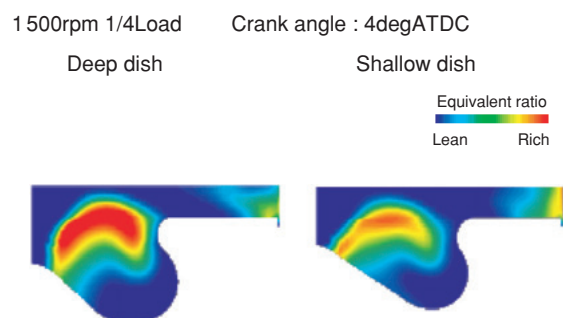


Fig. 2 Effect of combustion system modifications for mixture distribution

Moreover, expanding the bowl diameter promotes wider fuel spray distribution near the bowl wall surface, mitigating poor distribution.

The combustion chamber shape selected as a result is shown in Fig. 3.

These measures promoted air-fuel mixture homogenization, and combined with swirl control that responds to engine speed and load using a linear variable swirl control valve (SCV), PM under a fixed level of NO_x are dramatically reduced. Figure 4 shows a comparison of emission performance.

4.1.2. Reduction in NO_x emissions

NO_x emissions tend to increase accompanying increases in engine required load. In order to reduce NO_x emissions and minimize PM emissions, this engine increased EGR gas amounts by enhancing the cooling performance of the EGR cooler. However, there is the issue of increasing HC and CO emissions when the combustion temperature drops excessively due to the drop in the EGR gas temperature when cooling the engine. To address the matter, a new mechanism bypassing the EGR cooler was adopted. The EGR system is shown in Fig. 5.

In order to minimize the increase in HC and CO emissions due to a drop in combustion temperature when the water temperature is low, an EGR cooler bypass valve can be switched to the bypass side, and a drop in the EGR gas temperature is avoided. Then, by switching the valve to the cooler side when the water temperature rises, it is possible to reduce NO_x emissions without increasing HC and CO emissions.

As shown in Fig. 6, compared to the situation without an EGR bypass, it is clear that HC emissions are dramatically reduced in the low water temperature - low load range where the combustion temperature is also low. As the water temperature rises, the effect

of the EGR cooler bypass gradually decreases, and when the water temperature reaches a predetermined value, the valve switches to the EGR cooler side, to increase EGR.

4.2. Output Performance

Figure 7 shows the engine output performance for this engine. Among engines with the same displacement, this engine provides

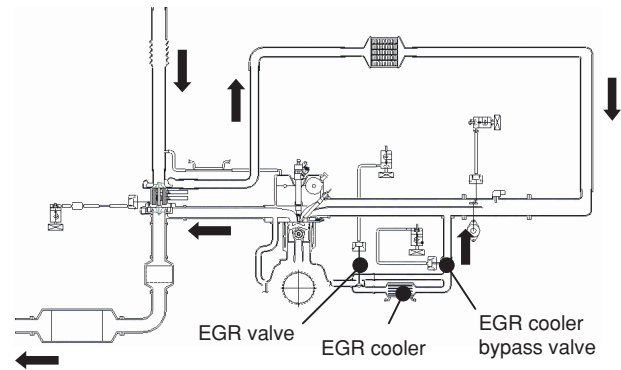


Fig. 5 Schematic diagram of EGR control system

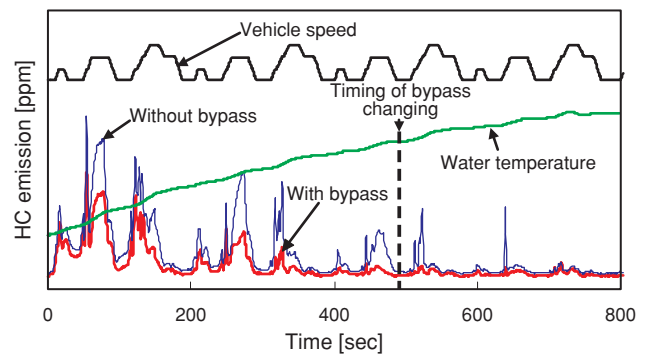


Fig. 6 Effect of EGR bypass system

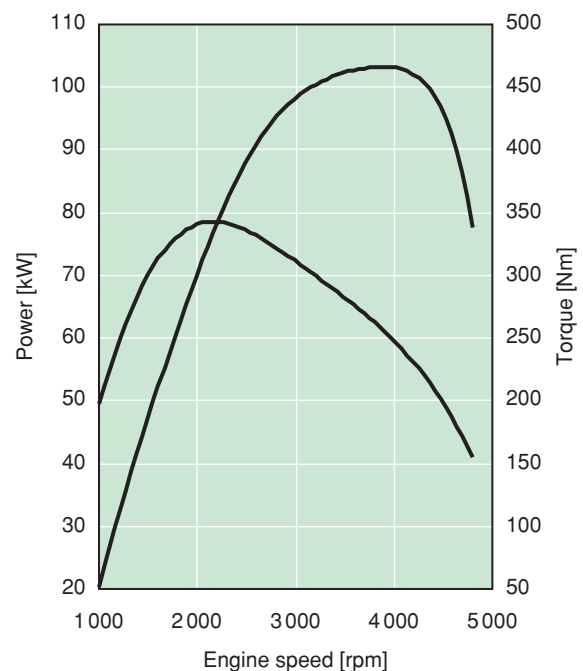


Fig. 7 Power curve of i-CTDi engine

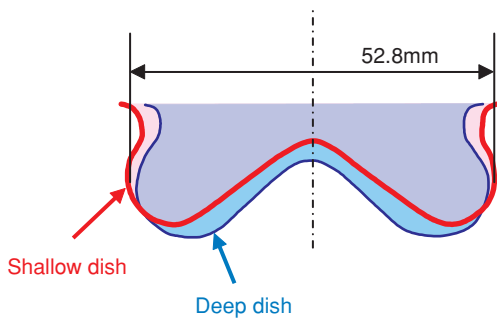


Fig. 3 Shape of combustion chamber

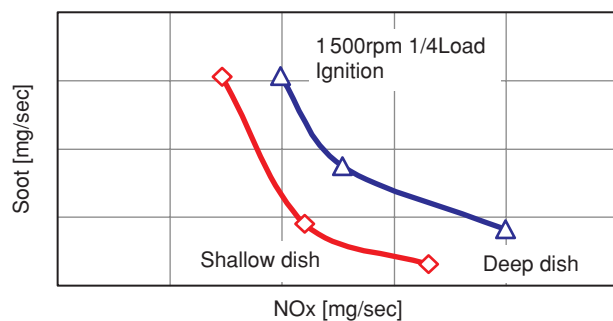


Fig. 4 Effect of combustion system refinement

the highest level of power performance in its class. The turbocharger system adopted a VGT, and optimum setting of the compressor enables optimum turbocharging in the full range. Boost pressure is controlled so it is at the target pressure, by opening and closing vanes, according to the boost pressure detected in the intake manifold. Negative pressure, electronically controlled by an Electric Vacuum Regulating Valve (EVRV), is used to open and close the vanes. The center housing is water cooled, and protects bearings and engine oil exposed to high heat. In addition, an air cooled intake cooler is provided, achieving a maximum turbo pressure of 130 kPa.

5. DPF System

5.1. System Outline

Figure 8 shows the basic configuration of the DPF. PM is collected, as exhaust gas passes through the DPF wall (pores of 9-13 μm).

Figure 9 shows an outline of PM collection and DPF regeneration in the DPF system. As the figure shows, the PM emitted from the engine is collected by the DPF, and when a specified amount is accumulated, the PM is burnt away due to the rise in exhaust temperature, regenerating the DPF.

Table 2 gives the basic general specifications of the DPF. The DPF pore diameter is determined based on PM collection capability. Porosity is determined based on regeneration performance. Diameter and capacity of DPF substrate are determined based on the vehicle life distance.

In order to create a system that demonstrates optimal DPF performance, without losing fuel economy or emissions performance, the following issues should be addressed.

- To enhance DPF regeneration performance during low load driving.
- To guarantee reliability when fuel dilutes engine oil.

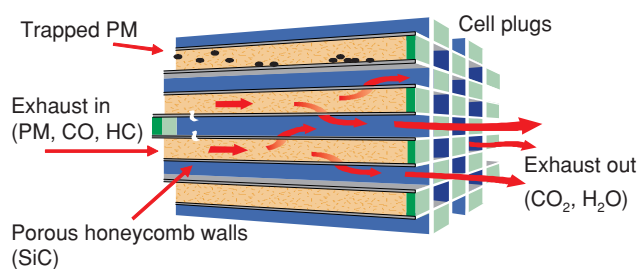


Fig. 8 Structure of DPF

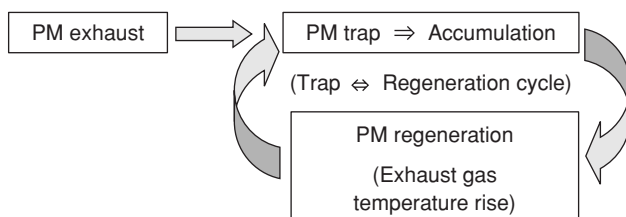


Fig. 9 Outline of PM regeneration

Table 2 DPF Specifications

DPF Size (mm)	$\phi 132 \times 228.6$
DPF Volume (liter)	3.1
Cell number (cells/in ²)	300
Pore diameter (μm)	11
Porosity (%)	42

5.2. DPF Regeneration Control

By forcibly increasing the DPF temperature to 550 °C or higher, using DPF regeneration control, the combustion speed of the accumulated PM is dramatically increased, and the PM burns in a shorter time.

Figure 10 shows the DPF regeneration control configuration. The PM emission amount calculated from engine speed, fuel injection quantity, intake air mass flow, and the PM combustion amount calculated from the DPF temperature are used to calculate the amount of PM accumulation. If the PM accumulation reaches the specified amount, DPF regeneration starts. During DPF regeneration, the DPF temperature rises, and when the PM combustion temperature is reached, the amount of PM accumulation is reduced, and when it reaches zero, DPF regeneration ends.

To make DPF regeneration possible under a wide range of driving conditions, it is necessary to increase the DPF temperature to 550 °C or higher. The methods are different for each driving range and control is performed according to different driving conditions. Figure 11 shows regeneration methods in each driving range.

In the full load range, the temperature making DPF regeneration possible is reached without regeneration control, and natural regeneration is possible.

At high loads, controlling the VGT vane towards the open side and reducing the intake air volume increases the exhaust temperature so that it reaches the DPF regeneration temperature.

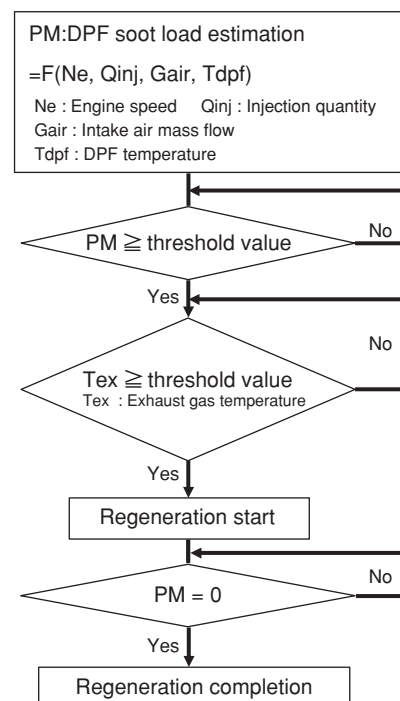


Fig. 10 DPF control software architecture

At medium loads, exhaust temperature rises by reducing the intake air volume through further throttling, and unburned fuel is supplied through post-injection in the expansion process. Utilizing the heat generated from the oxidizing catalytic converter located at the front of the DPF, the exhaust temperature reaches the DPF regeneration temperature.

At light loads, because the exhaust temperature does not reach the reaction temperature of the oxidation catalytic converter, the exhaust temperature is further raised by fuel injection carried out immediately after the main injection (after-injection). This enables DPF regeneration as the oxidation catalytic converter reaction temperature is reached.

Figure 12 shows the temperature shifts during DPF regeneration under actual driving conditions in European City mode. In traffic congestion, low exhaust temperatures are detected, and DPF regeneration stops. In suburban driving, the exhaust temperature rises and DPF regeneration starts. Once the DPF temperature reaches the PM combustion temperature, it is possible to maintain the DPF temperature even during congested driving.

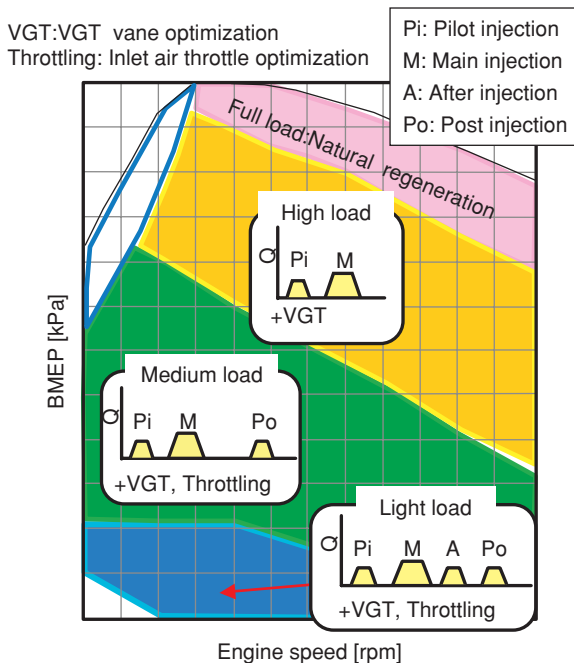


Fig. 11 Engine management strategy for DPF regeneration

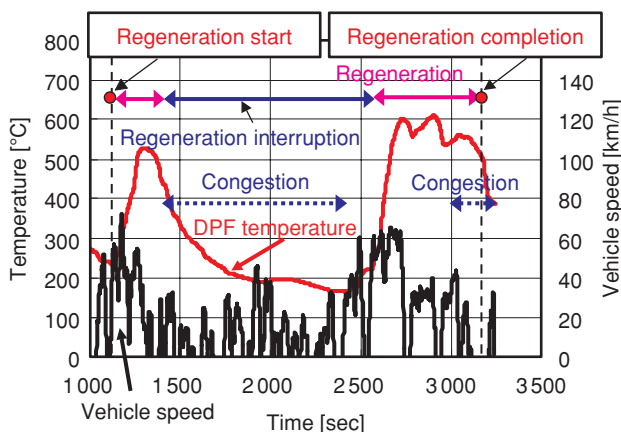


Fig. 12 DPF temperature in European city mode

In constant congested driving, DPF regeneration may not be possible and the driver is prompted by an indicator light to carry out DPF regeneration. The driver can complete DPF regeneration by driving for 10 minutes at 60 km/h or more.

5.3. Effect on Reliability (fuel dilution through post-injection)

When using post-injection during DPF regeneration, the unburned fuel that sticks to the sleeve wall becomes mixed in with the engine oil, which promotes deterioration such as a drop in viscosity. Therefore, as shown in Fig. 13, post-injection limits are established.

If a specific amount of PM has accumulated and DPF regeneration is carried out using post-injection, when the total post-injection amount reaches a specific limit, post-injection during DPF regeneration is terminated.

Then, after a specific distance or greater has been traveled, DPF regeneration post-injection resumes. Once DPF regeneration is complete, the post-injection limit is reset.

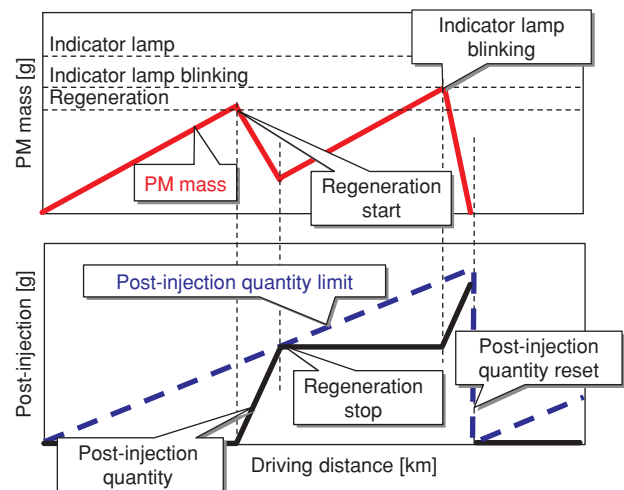


Fig. 13 Outline of post-injection limit control

6. Vehicle Performance

6.1. Emissions Performance

Figure 14 shows the emissions achieved. Through the aforementioned enhancements, PM and NO_x are dramatically reduced, and the vehicle is the first SUV to comply with EURO-IV standards. In addition, with the adoption of the DPF, PM was reduced to less than one-tenth of the EURO-IV regulation value. The resulting PM emissions value is in compliance with that of the Austrian Incentive standard, the most stringent worldwide at the present time.

6.2. Dynamic Performance

Output characteristics emphasize acceleration at low to medium speeds. From city driving through highway driving, the engine

exhibits high performance under a wide variety of driving conditions.

In combination with an optimized gear ratio, NEDC mode fuel consumption reaches 6.7 L/100 km. This fuel economy is best-in-class for an SUV diesel engine.

Figure 15 shows this fuel economy and power performance achieved.

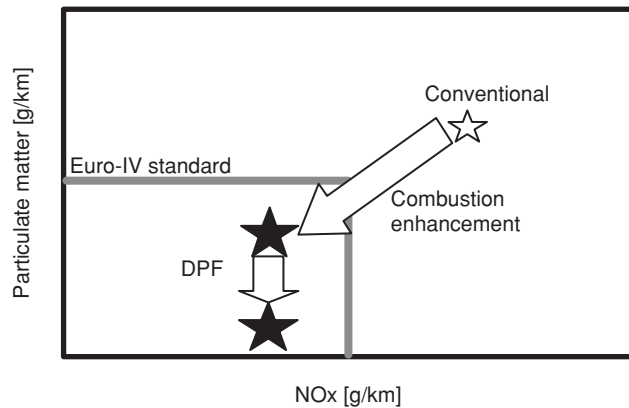


Fig. 14 Effect of combustion enhancement and DPF for exhaust gas emission

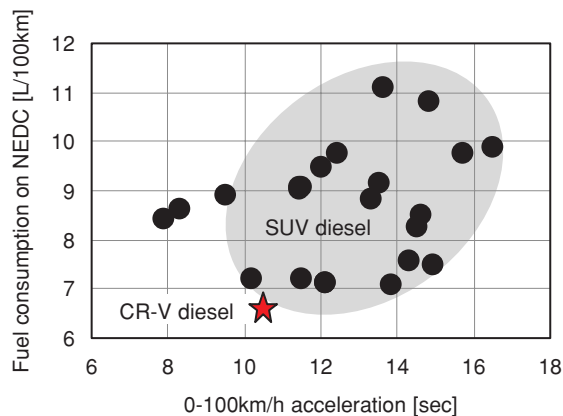


Fig. 15 Fuel consumption and acceleration performance of CR-V diesel

7. Conclusion

A diesel engine that has best-in-class SUV total performance was developed. The following results have been achieved through the development of this engine:

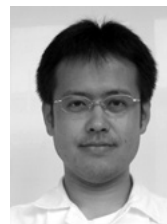
- (1) Modifications of the shallow dish combustion chamber shape and fuel injection nozzle as well as the use of a highly efficient EGR system made the engine the first SUV to comply with EURO-IV standards.
- (2) In terms of dynamic performance, quietness, and fuel economy, SUV best-in-class performances were also attained.
- (3) With the adoption of the DPF, PM emissions were reduced to less than one-tenth those of the EURO-IV regulation value.

- (4) By addressing the DPF system issues of enhancing DPF regeneration performance during low load driving and of fuel diluting the engine oil, Honda's first proprietary DPF system has achieved high performance and high reliability not seen previously.

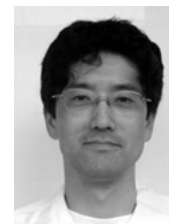
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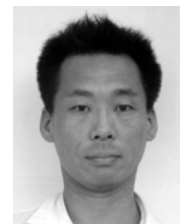
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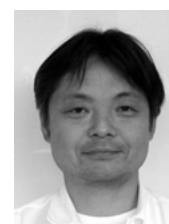
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