Development of New 2.4 L Direct-Injection Gasoline Engine

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ABSTRACT

A new 2.4 L i-VTEC 4-cylinder direct injection gasoline engine reconciling low CO_2 emissions performance with high power has been developed as part of a next-generation Honda engine series. The new engine employs a direct injection system provided with a high-pressure multi-hole injector positioned between the inlet valves. The inlet head port, combustion chamber shape, injector spray, and fuel injection control were optimized in order to realize homogeneous air-fuel mixture formation and enhanced combustion. Together with the reduction of friction through the modification of the engine framework, these innovations made it possible to realize a 4% increase in maximum power, a 12% increase in maximum torque, and a 5% or more increase in unit fuel efficiency. The use of this engine in the 2013 model year Accord, together with the employment of a high-efficiency CVT and modification of the vehicle body, has made it possible to realize an 11% increase in the EPA fuel economy label value and an emissions level corresponding to the LEV II SULEV level in the California Air Resources Board regulations. In addition, the use of a new engine framework that was reduced in weight while realizing stiffness in the areas necessary for noise and vibration performance made it possible to balance weight savings with the realization of an equivalent or higher level of noise and vibration performance than the previous engine.

1. Introduction

As concern over the protection of the environment increases, in the field of engine development attention is being focused on environmental performance technologies, as exemplified by the realization of increased fuel efficiency and reduced exhaust emissions, as an important agenda. At the same time, the driving pleasure offered by vehicles is also viewed as an important factor, and the development of groundbreaking technologies that reconcile dynamic performance with environmental performance is being pushed ahead. Honda has developed a K24 2.4 L 4-cylinder i-VTEC direct injection engine as a new 4-cylinder 2.4 L-class engine. The new engine adds in-cylinder direct injection (“direct injection” below) to the existing i-VTEC mechanism[(1)-(4)] in order to realize increased fuel efficiency, reduced exhaust emissions, and high power. This paper will discuss the new technologies employed in the new engine and its achieved performance.

2. Development Goals

Based on Honda’s concept of EARTH DREAMS TECHNOLOGY, revolutionary next-generation technologies that seek to balance further contribution to the realization of a low-carbon society with driving pleasure, the following targets were set for the development of the new engine in an attempt to reconcile environmental performance in the form of increased fuel efficiency and reduced emissions with dynamic performance offering driving pleasure:

(1) Dynamic low- and mid-speed torque to realize driving pleasure in the standard driving range
(2) Top-class fuel economy
(3) Emissions level satisfying the LEV II SULEV standard
(4) A balance between increased quietness and reduced weight

3. Overview of Engine and Applied Technologies

Figure 1 shows an external view of the engine, and Table 1 shows the main specifications of the new engine and a conventional 2.4 L engine. The core engine technology adopted in order to realize the development goals was in-cylinder direct injection, in an attempt to reconcile power performance with environmental performance by increasing charging efficiency and thermal efficiency against conventional port injection.

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Table 1 Engine specifications

Item	Developed	Previous
Engine code	K24W	K24Z
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × Stroke (mm)	87 × 99.1	87 × 99
Displacement (cm^3)	2356	2354
Compression ratio	11.1	10.5
Valve train	DOHC i-VTEC 16-valve	DOHC i-VTEC 16-valve
Valve diameter (mm) IN/EX	36/30	36/31
Cylinder offset (mm)	8	0
Fuel injection	Direct injection	Port injection
Fuel	Regular	Regular
Max. power (kW/rpm)	138/6400	132/6500
Max. torque (Nm/rpm)	245/3900	218/4300

Changes to the structure of the engine framework made it possible to realize an equivalent or higher level of noise and vibration performance than a conventional engine while reducing weight and increasing compactness. In the main drive system, the oil supply mechanism for the crank pin was increased in efficiency and friction reduction technologies were applied. The cylinder head was integrated with the exhaust manifold in order to reduce exhaust emissions and increase compactness. The modification of the configuration of the valvetrain mechanism reduced the valve angle despite the use of a conventional i-VTEC mechanism, and increased the compactness of the combustion chamber (Fig. 2), thus increasing the specific surface area of the combustion chamber, resulting in increased combustion efficiency. The shapes of the inlet head port and the combustion chamber were changed to realize the high level of flow motion necessary for homogeneous mixture formation. In the cam valve system drive mechanism, the positioning of a high-pressure pump drive cam for direct injection at the end of the exhaust cam and the use of a new chain tensioner mechanism have increased the reliability of the chain and reduced friction.

Fig. 1 K24W i-VTEC direct-injection engine

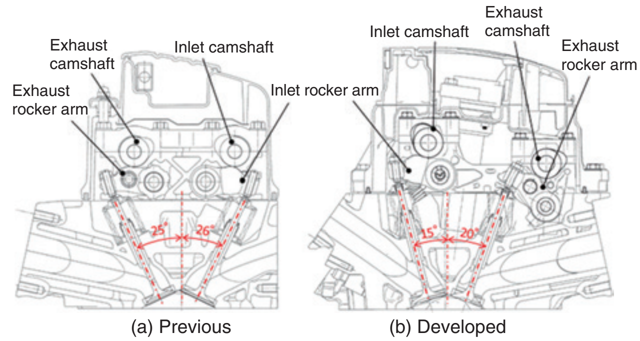


Fig. 2 Configuration of valvetrain and combustion chamber

4. Direct Injection System

4.1. Overview of Direct Injection System

Figure 3 shows an overview of the direct injection fuel supply system. In addition to realizing increased performance levels by means of high-pressure multi-stage fuel injection, this high-pressure fuel injection system was developed with consideration of sharing components with a V6 3.5 L engine, the present engine being the first in a series development. A compact packaging with the same ease of vehicle fitting as the port injection system used in the conventional system was realized.

A six-hole multi-hole injector was positioned between two inlet valves, and the form of the spray was optimized for stronger tumble motion, realizing stable combustion with minimal cycle fluctuation due to the formation of a homogeneous air-fuel mixture.

A high-pressure plunger pump able to pressurize the fuel to a maximum of 20 MPa was positioned at the end of the exhaust-side camshaft using a roller tappet. The use of optimum settings for four cam profiles and the realization of high-accuracy control have made it possible to realize fuel pressure control with high flexibility and good injector fuel spray performance. The optimization of the orifices in the fuel pipes has enabled the system to follow changes in fuel pressure during transient operation, helping to realize high-accuracy air-fuel ratio (A/F) control.

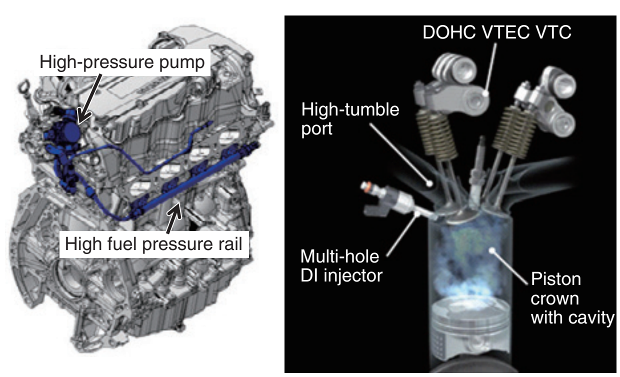


Fig. 3 High fuel pressure direct-injection system

4.2. Direct Injection Combustion Technologies

The concept established in order to achieve the goal of a balance between environmental performance and power established for the new engine was to realize stoichiometric combustion by means of homogeneous air-fuel mixture formation, with a focus on increasing charging efficiency, reducing knock and reducing exhaust emissions by means of direct injection. The high-flow motion inlet head port, multi-hole injector, and high-pressure fuel system were the core elements in the realization of homogeneous air-fuel mixture formation. Performance was improved and stable combustion was realized through the application of split injection, in order to enhance combustion and reduce soot emissions, and the realization of homogeneous mixture formation by means of more precise fuel injection control.

4.2.1. High-flow motion inlet head port

In order to realize homogeneous air-fuel mixture formation when using direct injection, it is necessary to increase the level of flow motion in the cylinders, but this reduces the relative flow rate coefficient, leading to the issue of balancing stronger flow motion with the high flow rate necessary for the realization of high power in a naturally aspirated engine. In order to balance these antagonistic performance elements, maximal use was made of the VTEC mechanism to optimize the balance between tumble and the flow rate coefficient in each cam lift range in order to satisfy the differing performance targets for each engine speed range. In concrete terms, the development aimed at a balance between a high tumble characteristic in the VTEC low-speed cam lift range, in order to realize a high level of flow motion in the low engine speed range, in which the flow energy of the intake air is low, and the high flow rate necessary to the realization of high power in the VTEC high-speed cam lift range. In order to attain this goal, in addition to modifying the shape of the inlet head port, a shroud was added to the combustion chamber. Figure 4 shows the shape of the combustion chamber with its shroud, while Fig. 5 shows the change in flow around an inlet valve produced by the shroud.

The shroud is formed on the outer circumference of the combustion chamber inlet valves, and controls the flow approaching the inlet-side sleeve. This makes the flow on the spark plug side the dominant flow, strengthening tumble mainly during low to medium lift, as shown in Fig. 6, thus realizing a high level of flow motion in the VTEC low-speed cam range. As Fig. 7 shows, because the effect of the shroud is minimal in the high lift range, and does not produce a decline in the flow rate coefficient, it is possible to realize a high flow rate coefficient in the VTEC high-speed cam range. In addition, tumble in the high lift range has been enhanced through the use of an inlet head port shape that significantly curbs the reduction in the flow rate coefficient, making it possible to realize, in collaboration with VTEC, a high level of flow motion across the entire range and the high flow rate coefficient necessary for high power. Figure 8 shows the tumble ratio produced by the inlet head port shape and the addition of the shroud wall and its effect on the flow rate coefficient. The enhancement of tumble by means of modification of the shape of the inlet head port normally involves a tradeoff, resulting as it does in a decline in the flow rate coefficient. The use of the shroud, however, has made it possible to balance both parameters in relation to the correlation line for the tradeoff between them.

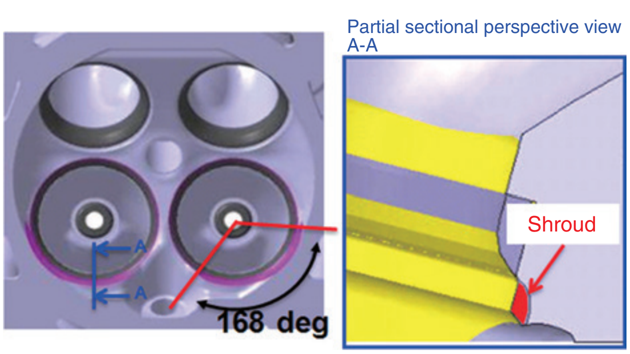


Fig. 4 Combustion chamber shape with shroud

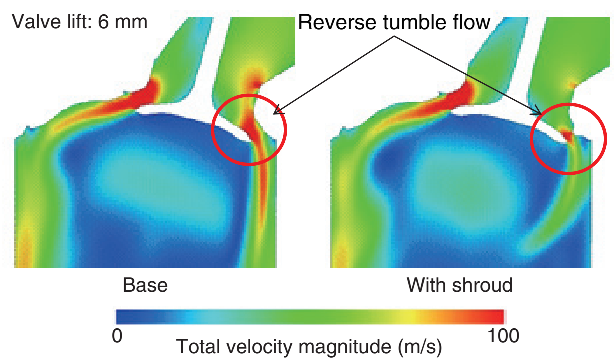


Fig. 5 Influence of shroud on air flow around inlet valve

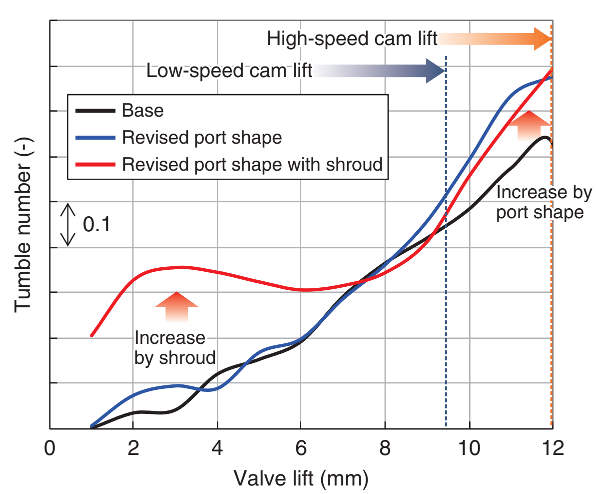


Fig. 6 Tumble flow intensity characteristics

4.2.2. Spray characteristic of direct injection injector

A six-hole multi-hole injector was employed as the direct injection injector. The spray characteristics of the injector were optimized. The position of the injector holes has a significant effect on formation of a homogeneous air-fuel mixture, in-cylinder flow motion and on the wetting of the cylinder walls. It was therefore necessary to attempt to realize a spray characteristic optimized for the strong in-cylinder flow motion achieved via the modification of the inlet head port. In selecting the injector spray characteristics, in addition to basic performance parameters such as power and fuel efficiency, combustion stability at low temperatures, soot production, and oil dilution were also taken into consideration as issues for direct injection. The spray characteristic was optimized on this basis using CFD and engine tests. Figure 9 shows the spray patterns employed in the study. Studies were conducted on Pattern A, designed for a high level of diffusion; Pattern B, designed to achieve a high level of flow motion via the effect of the spray in assisting flow motion; and Pattern C, designed to reduce wetting of the sleeve.

Figure 10 shows CFD results for the three injector configurations for (a) tumble ratio, (b) homogeneousness of air-fuel mixture, and (c) amount of wetting of the sleeve and pistons. Table 2 shows an overview of representative test results. A variety of changes, for example in combustion,

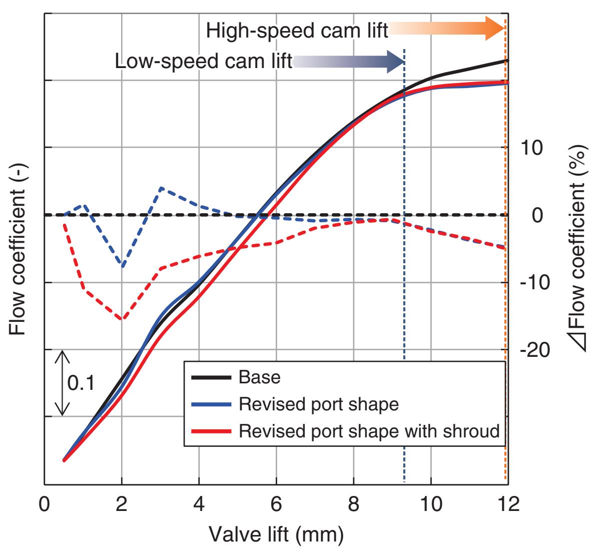


Fig. 7 Flow coefficient characteristics

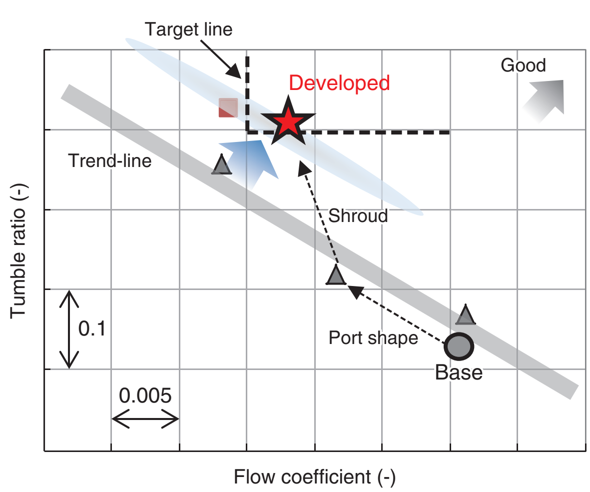


Fig. 8 Relationship of flow coefficient and tumble ratio

Table 2 Test results for difference in injector spray position

	Pattern A		Pattern B		Pattern C
WOT power	Base	+	1% Increase		Equivalent
BSFC	Base		Equivalent		Equivalent
Combustion stability	Base	+	Better		Equivalent
Exhaust soot	Base		Equivalent	-	Increase
Oil dilution	Base	+	3% Reduction	+	2% Reduction

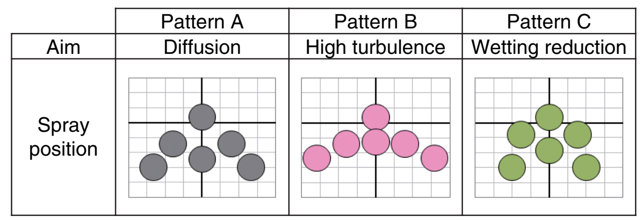


Fig. 9 Injector spray position

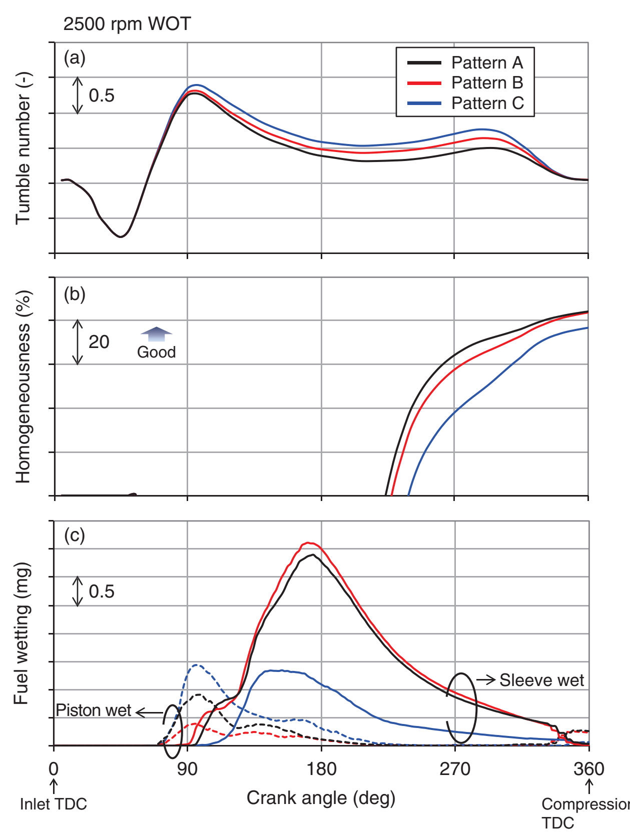


Fig. 10 CFD results for difference in injector spray position

were observed in both the CFD and engine test results. In comparison to Pattern A, Pattern B increased power at WOT due to an increased tumble ratio, and an increase in combustion stability was observed. While an increase in the tumble ratio was observed for Pattern C, no increase in power or change in combustion were obtained due to a decline in the homogeneousness of the air-fuel mixture, thought to be due to concentration of the spray in the center. An increase in soot production due to increased wetting of the pistons was also observed. Oil dilution was reduced for both Patterns B and C, but wetting of the sleeve increased in CFD results for Pattern B, and a correlation could therefore not be observed. The positions in which wetting of the sleeve occurred were isolated. Figure 11 shows results of wetting of the sleeve on the inlet and exhaust sides at bottom dead center during the inlet stroke and for oil dilution in the actual engine. A correlation can be observed between results for the amount of wetting of the sleeve on the inlet side and for oil dilution in the engine. This is thought to be because the temperature of the sleeve on the inlet side is low and there is little evaporation following wetting, and this tends to contribute to dilution. Based on the results discussed above, Pattern B was selected as the configuration of holes producing the optimum spray for the engine in development.

4.2.3. Direct fuel injection timing and injection pressure control

A number of methods of maximally realizing the merits of direct injection – greater freedom in injection timing, and the achievement of increased power and fuel efficiency through the use of multi-stage fuel injection – are available, including reducing the injection period by increasing fuel pressure and setting maximum and minimum injection amounts by increasing the range of fuel pressure control. A system using high fuel pressure and with a wide fuel pressure control range was therefore applied in the new engine. The range of fuel pressure control in the engine is 3.5 MPa to a maximum of 20 MPa, and cooperative control is applied to optimize injection timing and the number of injections in response to operating conditions including engine speed and engine load. CFD was used to study the effect of the high-fuel-pressure split injection realized through the optimization of fuel pressure and injection timing. Figure 12 shows changes in (a) the kinetic energy of turbulence in the cylinder, (b) A/F close to the spark plug, and (c) the homogeneousness of the air-fuel mixture in the cylinder. With the use of split injection, in-cylinder flow motion has been strengthened by the second injection at the commencement of the compression stroke, and increased stability of A/F close to the spark plug and increased homogeneousness of the mixture can be observed.

To maximize the effects of split injection, the fuel injection pressure, the timing of the first and second injections, and the ratio of splitting were optimized. Figure 13 shows the results of tests of optimized split injection in an actual engine. For a single injection, advancing the injection timing tends to increase combustion stability, but an increase in soot production due to increased wetting of the pistons becomes an issue, necessitating the use of high-accuracy injection timing settings. In the case of high-fuel-pressure split injection, robustness in relation to

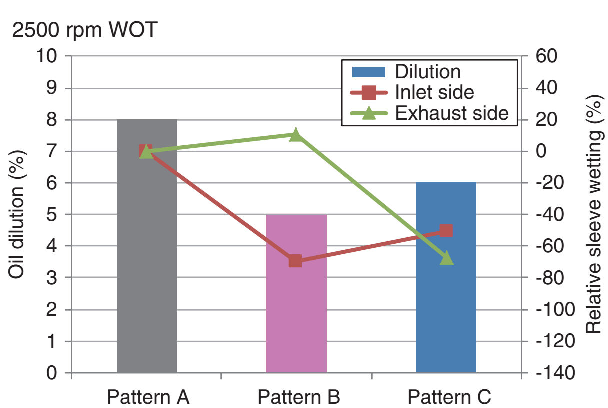


Fig. 11 Fuel wetting and oil dilution

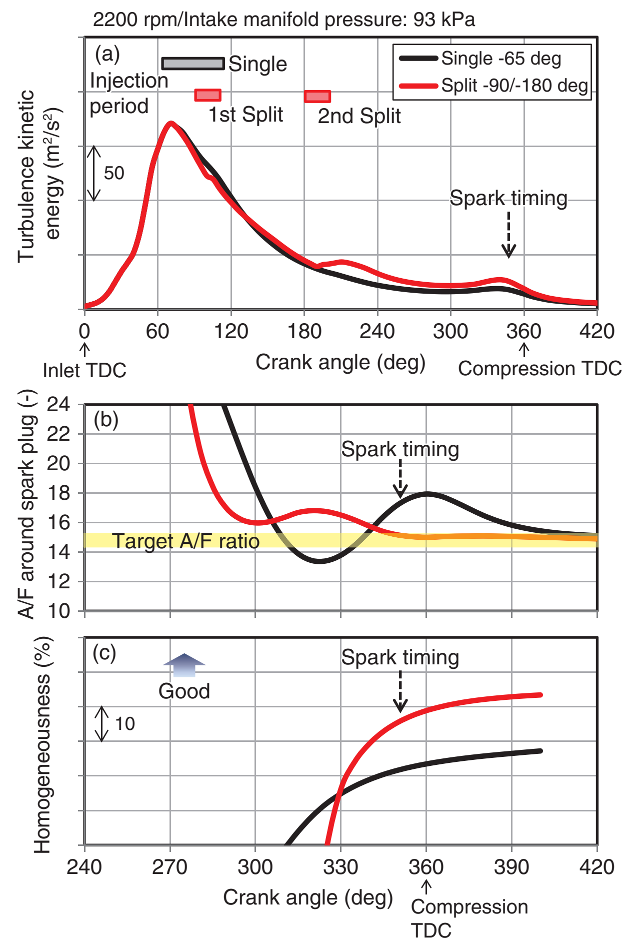


Fig. 12 CFD results for differences in injection control

soot production is increased, making it possible to increase combustion stability without increasing soot emissions. Flexibility in injection timing settings is also increased. These factors, in combination with the realization of increased combustion speed, have resulted in a reduction of more than 1% in fuel consumption (BSFC).

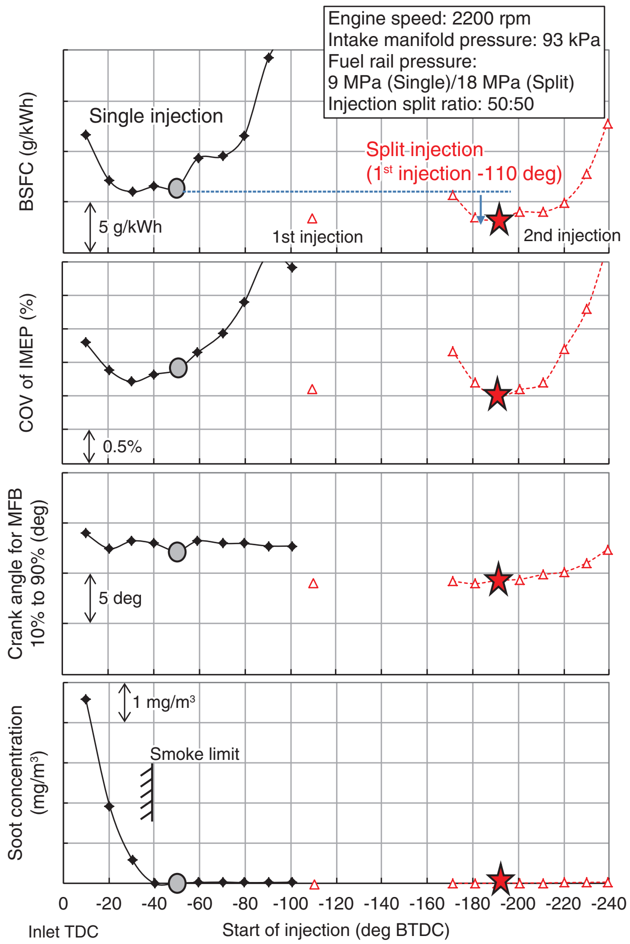


Fig. 13 Effect of fuel pressure and injection timing control

5. Technologies for Increased Power

Development of the new engine aimed towards the realization of a power characteristic in which low- to mid-speed torque was increased in order to boost dynamic performance in the standard operating range. The technologies employed to increase power are discussed in this section. In the direct injection system, in addition to an inlet head port designed to realize both a high level of in-cylinder flow motion and a high flow rate coefficient, high power was realized by increasing charging efficiency and reducing knock through optimization of the injector spray and injection control. Figure 14 shows the increase in power realized through the use of direct injection.

Figure 15 compares the power characteristics of the developed engine and the previous engine. The developed engine increases low-speed torque by 10% or more, maximum torque by 12%, and maximum power by 4% against the previous engine due to the application of the direct injection system discussed above and the following technologies designed to increase power:

(1) Use of an intake manifold with a built-in resonator to increase low- to mid-speed torque
(2) Realization of increased inlet and exhaust efficiency through the shape of the inlet head port, the integration of the exhaust manifold with the cylinder head, and the optimization of valve timing
(3) Reduction of knock through the use of a high-flow-motion port, increased compactness in the combustion chamber, and modification of the cooling system
(4) Friction reduction technologies

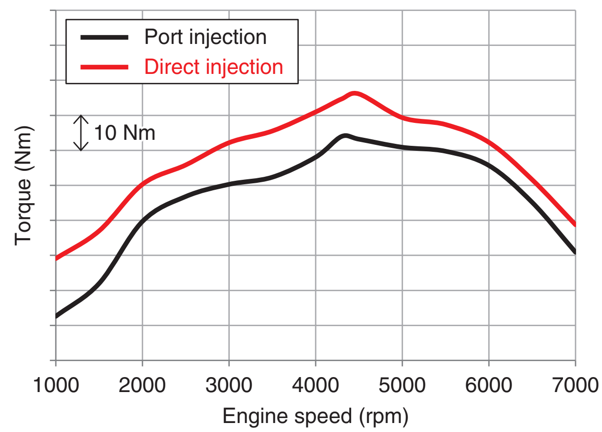


Fig. 14 Effect of direct injection

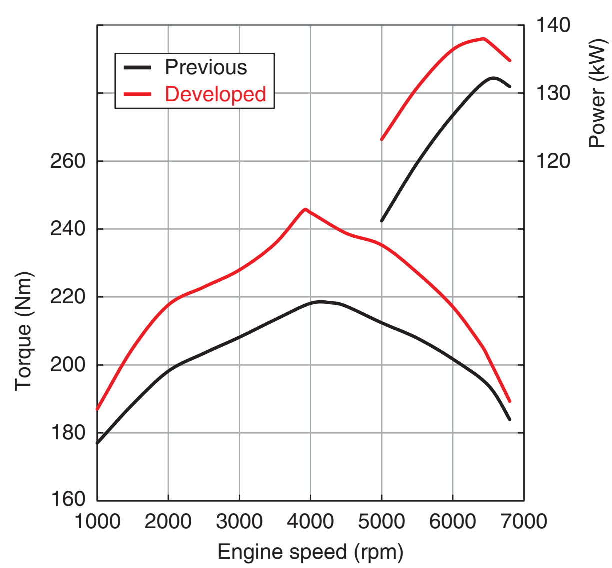


Fig. 15 Engine performance

6. Technologies for Increased Fuel Efficiency

6.1. Friction Reduction Technologies

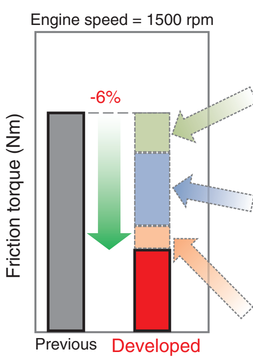
As Fig. 16 shows, the following technologies were applied to reduce friction by means of modification of the basic framework: the application of a double-arm chain tensioner, reduction of the surface roughness of the cam journals, optimized cylinder offset, the use of low-restraint oil seals, modification of the shape of the balance weight, the use of a concentrated supply configuration for journals #2 and #4, and the use of low-viscosity oil. The use of these friction reduction technologies has reduced friction by 6% against the previous engine.

6.2. Unit Fuel Consumption

Figure 17 shows BSFC characteristics at an engine speed of 1500 rpm. As a result of the application of the friction reduction technologies discussed above and the increased combustion efficiency achieved by means of direct injection, in addition to the optimization of split direct injection control in the high-load range, unit fuel consumption has been reduced by 5% or more against the previous engine.

6.3. Fuel Efficiency in an Actual Vehicle

The use of a new CVT made it possible to reduce engine speed while driving and freely set engine speed. Powertrain control was optimized with consideration of the enhanced torque characteristic achieved by means of direct injection, the BSFC characteristic, and the transmission efficiency of the transmission. As Fig. 18 shows, it was possible to reduce engine speed against the previous AT model in LA4 mode, increasing fuel efficiency. In addition to the increased fuel efficiency achieved by means of these innovations in the powertrain, the application of a number of measures including enhancing the aerodynamics of the vehicle body, reducing weight, and reducing rolling resistance has made it possible for the developed engine to increase EPA fuel efficiency by 11% against the previous engine, realizing the top-class fuel economy of 30 mpg.



Items (contribution)	Friction reduction methods
Valvetrain drive (29%)	Double-arm chain tensioner
	Surface roughness reduction on cam journals
Reciprocating and rotating part drive (54%)	Cylinder offset
	Low-restraint oil seal
	Modification of balance weight design
Others (17%)	Concentrated on supply structure for #2 and #4 journals
	Low-viscosity oil

Fig. 16 Friction reduction technologies

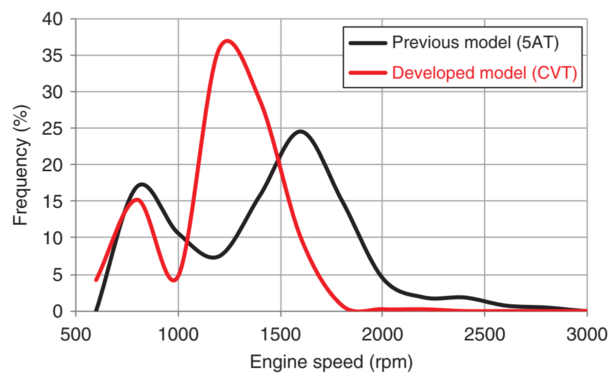


Fig. 18 Engine speed frequency in LA4 mode

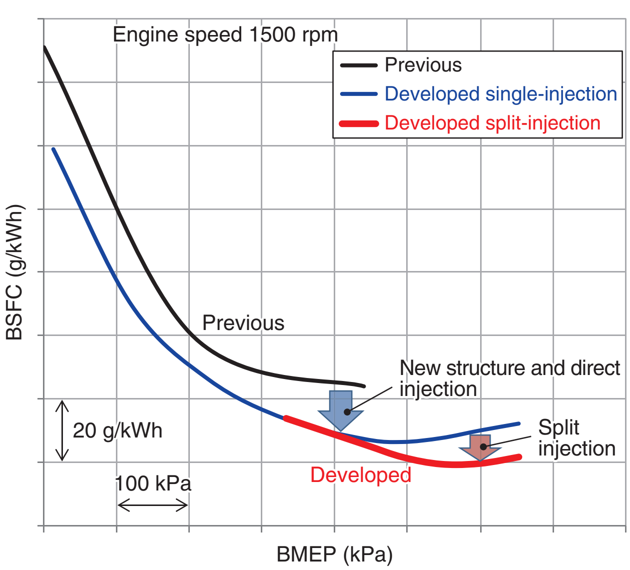


Fig. 17 BSFC characteristic

7. Technologies to Reduce Exhaust Emissions

7.1. Overview of Technologies to Reduce Exhaust Emissions

In order to conform to the SULEV category of the US LEV II regulations, one of the world's most stringent exhaust emissions standards, the following technologies were applied in the new engine in an attempt to reduce feed-gas emissions and increase the efficiency of exhaust gas after-treatment:

- Reduction of feed-gas emissions through optimization of direct injection combustion and modification of combustion chamber
- Enhancement of catalyst purification efficiency through modification of exhaust gas flow
- Use of a new catalyst balancing low cost and high performance

7.2. Enhancement of Exhaust Gas Flow

In order to make maximal use of the purification efficiency of the catalyst while controlling catalyst degradation, it is necessary to introduce the exhaust gas to the catalyst in a uniform manner. The shape of the front cone is important in realizing this goal. The use of front exhaust rather than the rear exhaust employed in the previous engine increased the flexibility of design of the front cone, making it possible to introduce a more uniform exhaust gas flow to the close-coupled catalyst, as shown in Fig. 19. It was also possible to install the Universal Exhaust Gas Oxygen sensor in the optimal position, helping to enable the realization of more accurate A/F control.

7.3. Low-precious-metal Catalyst

Reduction of the amount of precious metals used in the catalyst, in particular rhodium (Rh), which is produced in only extremely small quantities, was studied in order to contribute to the preservation of global environment and resources. Rh displays good performance in the purification of exhaust gas. Substitution of palladium (Pd), which increases the speed of absorption and desorption of oxygen, for part of the Rh in the newly developed catalyst made it possible to reduce the amount of precious metals, and particularly Rh, in the catalyst overall. Figure 20 shows a comparison of the amount of precious metals used and emissions performance for the previous and the newly developed catalysts. Despite the fact that it uses 22% less precious metals and 50% less Rh than the previous catalyst, the new catalyst achieves a higher level of purification performance. This has made it possible to conform to the SULEV category of the US-LEVII regulations while using a reduced amount of precious metals and Rh than the previous catalyst.

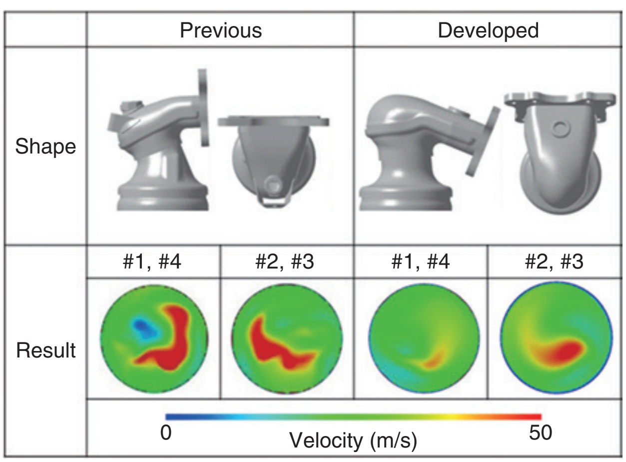


Fig. 19 Front gas feed distribution

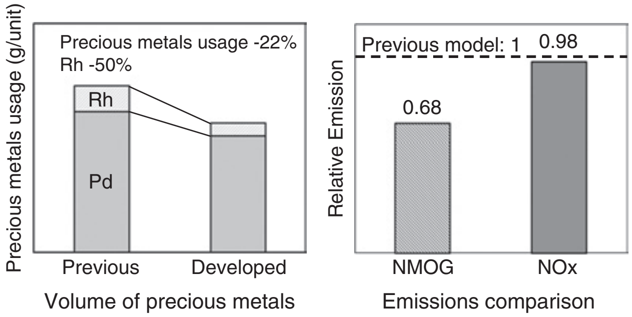


Fig. 20 Comparisons of volume of precious metals and emissions

8. Technologies for Reduction of Noise and Vibration

A transfer path analysis using principal component regression (PCR-TPA)[5, 6], a technique used to analyze phenomena such as cabin noise during acceleration, was applied to the new engine in an attempt to balance NV performance with weight savings. The transfer paths for engine vibration produced by combustion excitation force can be broadly divided into three:

(1) A transfer path from the combustion chamber directly to the cylinder head.
(2) A transfer path to the cylinder block, via the pistons.
(3) A transfer path to the lower block integrated with the crank bearings and surface of the outer wall, via the crankshaft.

Cylinder head vibration, cylinder block vibration, crank bearing vibration, and engine vibration at the engine mounts were measured simultaneously and a PCR-TPA was conducted. Figure 21 shows the analysis results for the ratio of contribution to transfer. The results of the analysis showed that the ratio of contribution of the areas around the crank bearings to the transfer of vibration to the engine mounts was high, while other parts displayed a low contribution.

Based on these results, the same lower block configuration integrated with the crank bearings and the exterior wall by means of the rudder frame employed in the previous engine was used in the new engine to help ensure stiffness around the bearings. In addition,

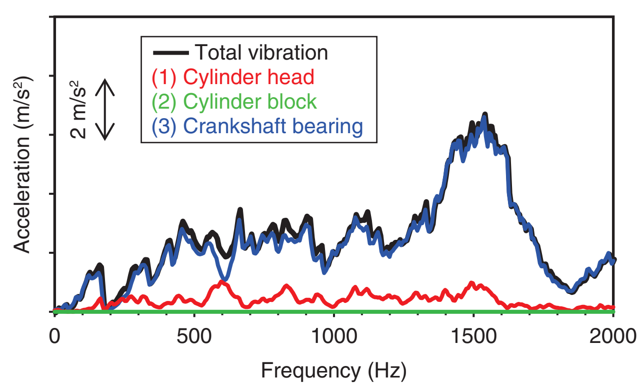


Fig. 21 Effect on PCR-TPA vibration transfer

as shown in Fig. 22, the weight of the cylinder block, which displayed a low contribution to the transfer of vibration, was reduced by 10%. Figure 23 shows the positioning of maximum power and the reduction of weight of the cylinder block in the developed engine against the previous engine. The realization of a balance between high stiffness and reduced weight, as described above, made it possible to achieve noise and vibration performance equal to or higher than the previous engine (Fig. 24), while reducing the weight of the engine framework by 6%.

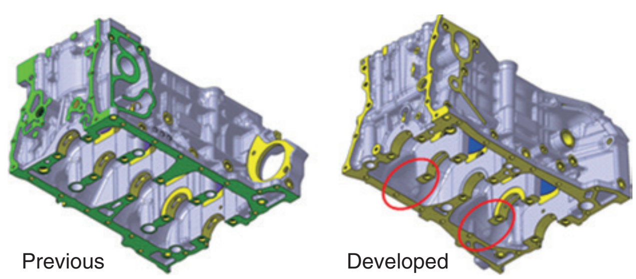


Fig. 22 Cylinder block weight reduction

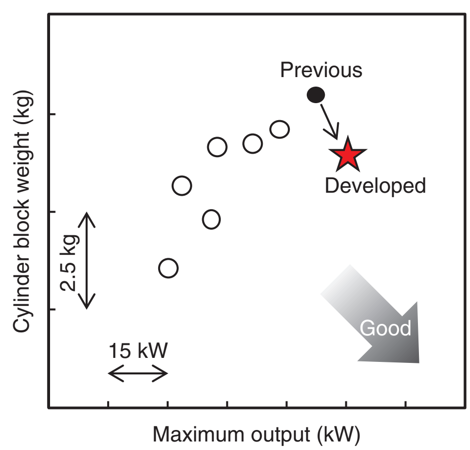


Fig. 23 Cylinder block weight and maximum output

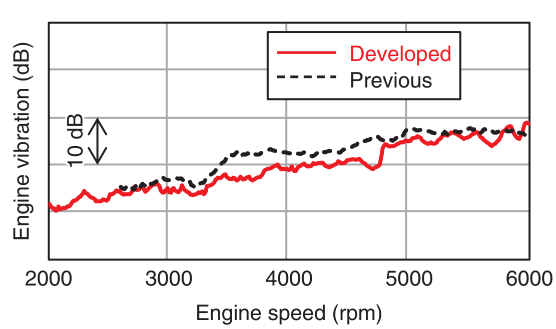


Fig. 24 Vibration level at end of engine mount bracket under full load

9. Conclusion

In the development process of a new 4-cylinder 2.4 L direct injection engine, CFD was employed to study the specifications of direct injection combustion technologies, resulting in the realization of enhanced combustion by means of optimization of the inlet head port, combustion chamber shape, the injector spray, and injection control. In addition to direct injection combustion technologies, the use of a new framework made it possible to employ friction reduction technologies and emissions reduction technologies, producing the following results:

(1) The new engine has achieved a 10% increase in low-speed torque, a 12% increase in maximum torque, a 4% increase in maximum power, and a 5% increase in unit fuel efficiency against the previous engine.

(2) The reduction of engine speed with the use of a CVT and the optimization of the engine operating line, in addition to the enhancement of unit fuel efficiency, helped to enable the achievement of a EPA top-class fuel economy of 30 mpg.

(3) The reduction of feed gas emissions and the optimization of the exhaust system in the new engine made it possible to realize US LEV II SULEV-level emissions performance.

(4) In line with modification of the engine framework, a high level of stiffness was efficiently realized in combination with a reduction in weight by means of analysis of contribution to vibration transfer, with the result that the engine was increased in compactness and reduced in weight by 6% against the previous engine while realizing an equivalent or higher level of noise and vibration performance.

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