

Development of New 1.6 L 2-stage Turbocharged Diesel Engine for Honda CR-V

Junichi HATANO*
Taro TABUCHI*

Ken NISHIMORI*
Naoto KITAYAMA*

Hiroyuki FUKUSHIMA*
Yoshinori ISHIHARA*

ABSTRACT

This newly developed engine is based on a downsized 1.6 L 88 kW (55 kW/L) engine, with dynamic performance aimed to replace the previous 2.2 L 110 kW (50 kW/L) diesel engine. The new engine uses a 2-stage turbocharger to achieve high power while maintaining the maximum commonality with the structure of the 1.6 L 88 kW diesel engine. The bearing cap, head gasket and other parts have been specially designed to reinforce the engine structure, realizing high-specific power of 118 kW (74 kW/L). In addition, a newly developed NO_x storage catalyst is used, complying with the European EURO 6 emission standards. Technologies for enhancing fuel economy include further reduction of mechanical friction and enhancement of combustion efficiency by combustion calibration. These technologies were applied to develop a EURO 6-compliant power unit that provides high power with low fuel consumption, and this power plant was mounted in the 2015 CR-V for Europe.

1. Introduction

Recently, concern for environmental issues such as global warming and energy resources is growing, and there are strong social demands for reduction of CO₂ emissions from passenger vehicles. Demands are also increasing for dynamic performance, and the further evolution of diesel engines that have both good drivability and low-fuel-consumption performance is anticipated from these viewpoints. In this background, Honda developed a 2.2 L inline 4-cylinder i-CTDi turbocharged diesel engine⁽¹⁾ in 2003, and mounted it in the Accord for the European market. Since then, the same diesel engine has been used in multiple models such as the CR-V and Civic. Honda developed an i-DTEC diesel engine^{(2), (3)} in 2008 as a second-generation 2.2 L engine. This engine had completely new combustion system specifications, such as the compression ratio and injector, which enabled compliance with the European EURO 5 emission standards (EURO 5) and also enhanced fuel economy performance. The CR-V released in 2009 was equipped with this i-DTEC diesel engine and achieved CO₂ emissions of 149 g/km in the New European Driving Cycle (NEDC) mode.

Honda announced the “EARTH DREAMS TECHNOLOGY” engine series in November 2011, which offers next-generation powertrain efficiency to provide

a superior combination of fuel economy and dynamic performance. As the first step, a 1.6 L 88 kW i-DTEC diesel engine was released as a third-generation diesel engine and mounted in the Civic for Europe at the start of 2013⁽⁴⁾. This engine was realized by completely reforming and downsizing the conventional 2.2 L diesel engine^{(5), (6)}, which made it the lightest-weight engine in its class known to date and increased the power train efficiency by measures such as reducing friction to a level comparable to that of a gasoline engine. This resulted in a EURO 5-compliant vehicle with top-class fuel economy.

In addition to the low fuel consumption concept, this development aimed to further enhance driving performance, and increased the power based on a 1.6 L diesel engine. The basic parts of the main engine structural components, such as the aluminum cylinder block with an open deck structure⁽⁷⁾, are shared with those of the existing 1.6 L engine. A CR-V equipped with the new engine complied with the European EURO 6 emission standards (EURO 6), and achieved the fuel economy performance of CO₂ emissions of 129 g/km in NEDC mode even while possessing driving performance enabling replacement of the 2.2 L diesel engine. This paper describes the technologies applied to the new engine to increase power, comply with EURO 6, and enhance fuel economy.

* Automobile R&D Center

Table 1 Engine specifications

	2.2 L 110 kW (150 PS)	1.6 L 88 kW (120 PS)	1.6 L 118 kW (160 PS)
Engine	Inline 4-cylinder DOHC 4 valves		
Bore x Stroke	φ 85 x 96.9 mm	φ 76 x 88 mm	
Displacement	2199 cm ³	1597 cm ³	
Compression ratio	16.3	16.0	
Cylinder block	Advanced semi-solid casting technology (ASCT) closed deck	High pressure die-casting (HPDC) open deck	
Max. torque	350 Nm /2000-2750 rpm	300 Nm /2000 rpm	350 Nm /2000 rpm
Max. power	110 kW(150 PS) /4000 rpm	88 kW(120 PS) /4000 rpm	118 kW(160 PS) /4000 rpm
Crankshaft main bearing diameter (mm)	φ 62	φ 55	φ 55
Conrod bearing diameter (mm)	φ 51	φ 39	φ 42
Balancer	Applied	N/A	Applied
Turbocharger	Variable geometry turbocharger, Honeywell GT14	Variable geometry turbocharger, Honeywell GT12	Serial-sequential 2-stage turbocharger, Honeywell GT10/GT15
Common-rail fuel injector	Piezo (Max. 180 MPa) φ 0.123 mm x 7 holes	Solenoid (Max. 180 MPa) φ 0.114 mm x 8 holes	
EGR system	HP hot EGR of HP cooled EGR	HP hot EGR and/or LP cooled EGR	
Aftertreatment	DOC and DPF	NSC and DPF	NSC and DPF
Emissions	EURO5		EURO6
Vehicle	CR-V 4WD	CR-V 2WD	New CR-V 4WD
Fuel consumption (NEDC)	149 g/km	119 g/km	129 g/km

2. Overview of Newly Developed Engine

Table 1 lists the main specifications of the new engine and Fig. 1 shows the engine system layout. The new engine takes into account commonality with the engine frame of the previously released 1.6 L 88 kW i-DTEC diesel engine⁽⁷⁾. The main parts share common combustion system specifications, such as the piston combustion chamber design and the injector⁽⁸⁾, and the engine is equipped with a low-pressure exhaust gas recirculation (LP-EGR) system⁽⁸⁾,⁽⁹⁾ as an emission control device. The three technical items noted below as features of the new engine were set as development concepts.

- (1) A serial-sequential 2-stage turbocharger is used to increase power. In addition, the head gasket, bearing cap and reciprocating parts use special high-power designs allowing it to withstand the in-cylinder pressure boosted by supercharging.
- (2) A newly developed NO_x storage catalyst is used to achieve compliance with EURO 6.
- (3) Turbocharging specifications that take into account reduced pumping loss are used, mechanical friction has been further reduced⁽¹⁰⁾ and combustion calibration has been optimized in order to enhance fuel economy.

The following chapters describe the details of these technologies.

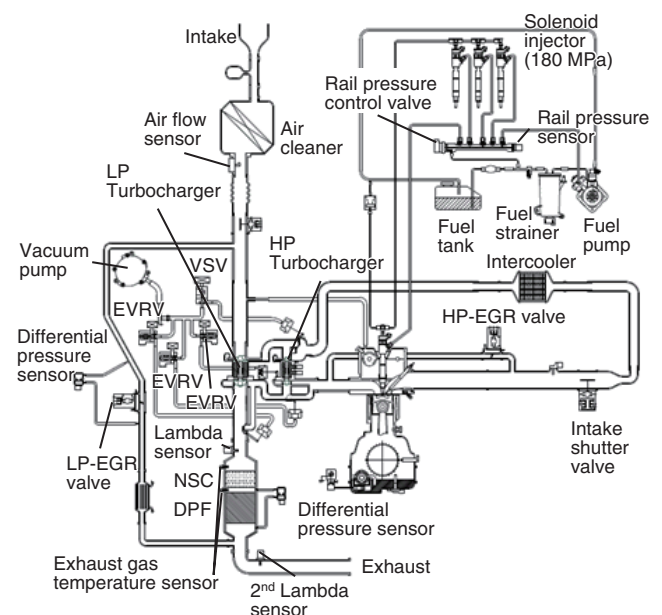


Fig. 1 Engine system layout

3. Technologies Applied to the Newly Developed Engine

3.1. High Power Using a 2-stage Turbocharger

When increasing the power it is necessary to secure an intake air flow corresponding to the target power, so the turbocharger size should be appropriate. Figure 2 shows a concept diagram related to turbocharger size selection. Figure 2 also shows an image of a compressor map obtained from the corrected air flow and pressure ratio of the turbocharger. To increase the specific power, the required air flow necessarily becomes larger than that of the single turbocharger utilized in the previous 1.6 L 88 kW model, so the turbocharger size increases. However, there was the issue that the boost performance, fuel economy performance and transient response performance under low-engine-speed, low-load operating conditions are lower than those of a compact turbocharger^{(10), (11)}.

To address these issues, the new engine uses a 2-stage turbocharger made by Honeywell, which is the first 2-stage turbocharger used by Honda. Figure 3 shows the appearance. The low-pressure-stage turbocharger (LP turbocharger) needs to satisfy power performance of 118 kW, so a size that secures sufficient air flow should be selected as shown in the image in Fig. 2. Therefore, a GT15 with a maximum supercharging pressure of 2.98 bar and a maximum turbine speed of 226000 rpm was used. In addition, a GT10 with a maximum turbine speed of 290000 rpm was selected for the high-pressure-stage turbocharger (HP turbocharger) as a compact turbocharger with the surge limit shifted to the high-power-ratio side compared to the 88 kW single turbocharger in order to secure acceleration performance from the low-engine-speed range. Here, the GT10 turbocharger is not a wastegate valve (WGV) type, and instead uses a variable geometry turbine (VGT)-type turbocharger with a structure that enables the turbine operating gas flow to be varied as shown in Fig. 4.

Figure 5 shows the approach toward selecting the HP turbocharger. This figure shows the effect of the turbocharger specifications on NEDC mode fuel

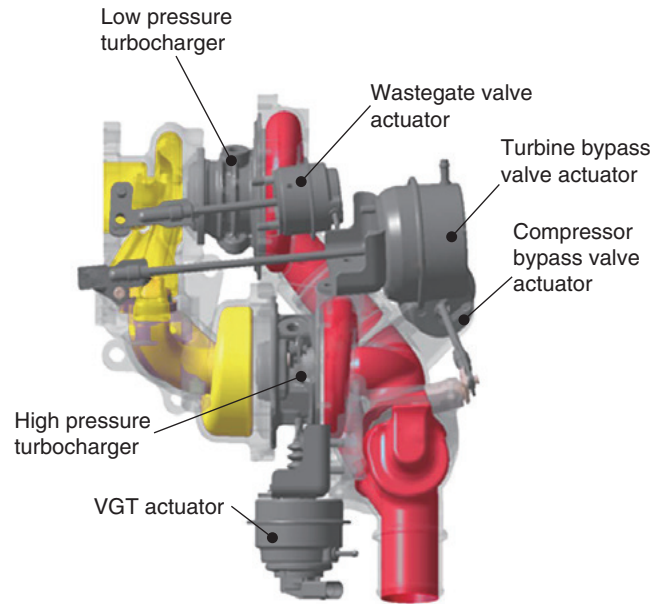


Fig. 3 Overview of 2-stage turbocharger

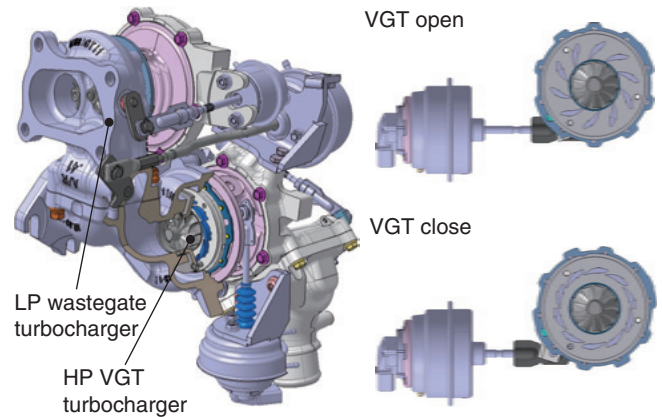


Fig. 4 Structure of VGT

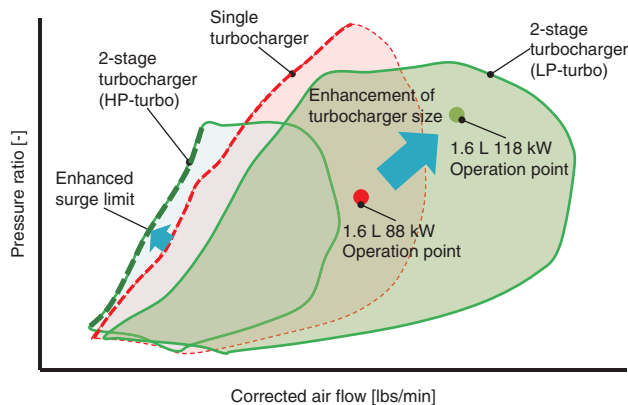


Fig. 2 Concept for determining turbocharger size

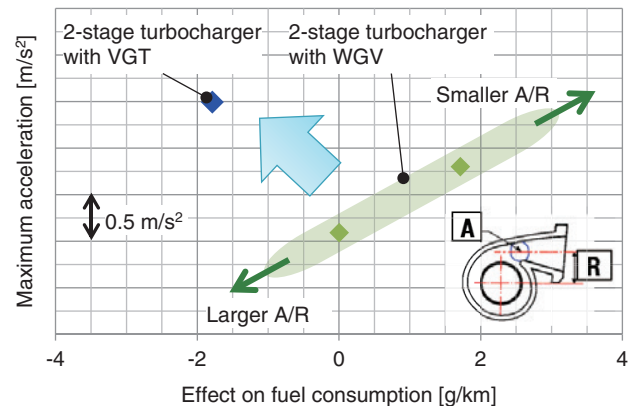


Fig. 5 Effect on dynamic performance and fuel consumption between WGV and VGT for HP turbocharger system

consumption on the horizontal axis, and the peak acceleration when accelerating with the throttle fully open in 3rd gear on the vertical axis. The typical 1.6 L-class 2-stage turbocharger structure performs boost control using a WGV on both the low-pressure and high-pressure sides. However, when a fixed turbine is used in the HP turbocharger, acceleration performance and the effect on fuel economy due to pressure loss have a trade-off relationship according to the selected ratio (A/R) of the sectional area (A) at the turbine inlet and the turbine wheel radius (R), which is a size index, and it is a challenge to realize both performances.

Therefore, the newly developed engine used a VGT-type turbocharger as the HP turbocharger of a mass-produced 2-stage turbocharger for a 1.6 L-class passenger vehicle, which is the first such case known to date. This simultaneously secured smooth acceleration performance by increasing supercharging performance at low engine speeds, and enhanced fuel economy performance by reducing pumping loss in the HP turbocharger operation range. The use of a VGT type enables obtaining the target supercharging pressure by setting an arbitrary vane angle in accordance with the operating conditions. This makes it possible to approach the exhaust backpressure of a single turbocharger in NEDC mode, and contributes to pumping loss reduction. Figure 6 compares the backpressure and shows the fuel consumption reduction effects of each turbocharger control system. The VGT type enabled reduction of the back-pressure at the same required boost pressure compared to the WGV system, and effectively reduced CO₂ emissions in NEDC mode by 3.5 g/km.

Figure 7 shows a schematic diagram of the 2-stage turbocharger used. The valve configuration used to

switch the HP turbocharger and LP turbocharger locates a compressor bypass valve (CBV) for bypassing the HP turbocharger compressor on the intake side, and a turbine bypass valve (TBV) for bypassing the HP turbocharger turbine on the exhaust side. The boost pressure is controlled by operating the four CBV, TBV, VGT and WGV devices in accordance with the engine operating range.

Here, Fig. 8 shows how each valve operates in accordance with the operating conditions. At low engine speeds, the boost pressure is controlled using only the VGT, and the other valves are all closed [Fig. 8 (a)]. In the medium engine speed range, once the VGT is fully opened, the supercharging pressure is controlled by the TBV, and the CBV and WGV are closed [Fig. 8 (b)]. Then, after the TBV has also opened fully, the boost pressure is controlled by the LP turbocharger WGV, and the CBV also opens so

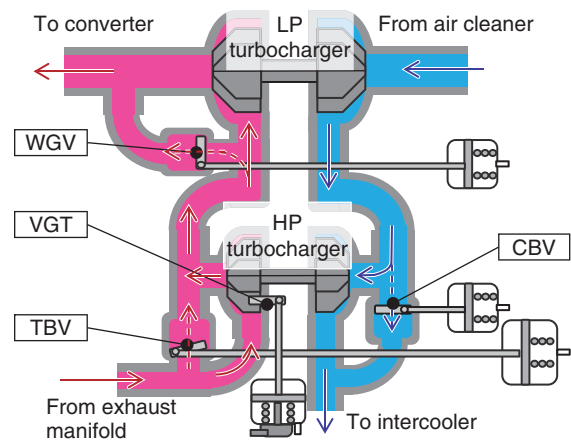


Fig. 7 Diagram of 2-stage turbocharger

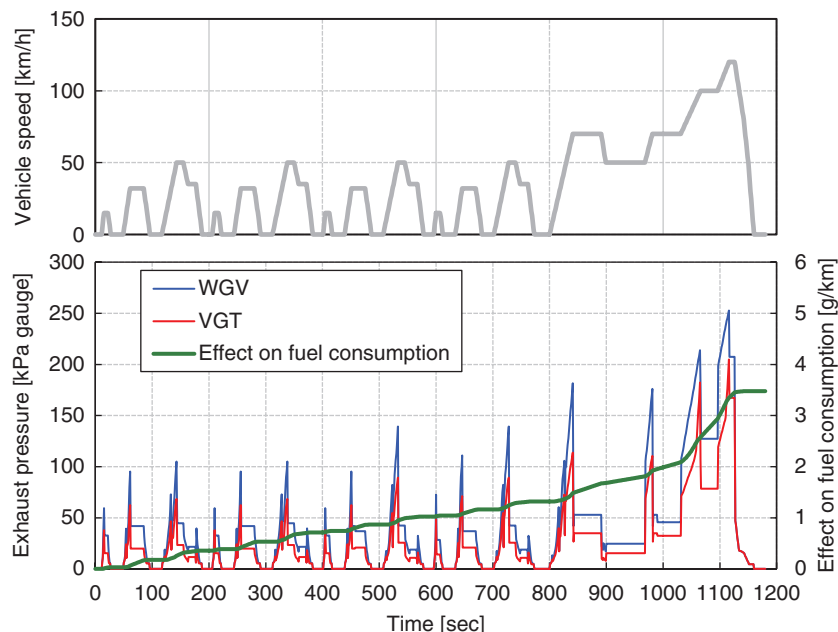


Fig. 6 Effect of pumping loss reduction between VGT and WGV

that the boost pressure is controlled by the LP turbocharger alone [Fig. 8 (c)]. The transition between each range is realized by model-based valve collaborative control.

3.2. Engine Structure that Supports High Power

Two performances are required of the hardware when increasing the power. The first requirement is an engine frame strength capable of withstanding the increase in in-cylinder pressure due to higher boost. For this reason, the connecting rod bearing diameter was increased from $\phi 39$ for the 1.6 L 88 kW model to $\phi 42$ to support the increased combustion load. An increase to 118 kW was anticipated when designing the 88 kW specifications, so a common engine block was used with a main journal diameter of $\phi 55$. Other changes to reinforce the engine frame include increased bearing cap stiffness and changes to the seal structure and head gasket materials.

The second performance required of a high-power engine frame is countermeasures for the increased thermal load. The layout of the engine oil cooling channels that cool the pistons was optimized, and the cooling jet flow was increased from the standard 1.5 L/min to 3.8 L/min to cool interbore temperature. The cooling jet flow rate increase was kept at the minimum required with fuel consumption in mind. In addition, the valve timing of the previous model was designed to reduce the pumping loss on the low-engine-speed side and enhance fuel economy during low-to-medium-load driving. In contrast, the new engine design increases the intake valve-opening angle to support high output, as well as the intake and exhaust valve lift amounts to increase the volumetric efficiency at the power point. This enabled enhancement of fuel economy performance at all loads, reduced the excessive thermal load to the cylinder block and cylinder head, and helped to withstand high

specific power.

Adoption of an engine frame that supports higher boost and increased power output as described above enabled the newly developed engine to achieve a maximum torque of 350 Nm at 2000 rpm and maximum output of 118 kW at 4000 rpm as shown by the power and torque curve in Fig. 9.

3.3. Technology for EURO 6 Compliance

The new engine has the maximum commonality with the 1.6 L 88kW engine specifications, enabling simultaneous achievement of high power and low cost. For this reason, the fuel injection system specifications (number of nozzle holes, nozzle hole diameter, nozzle cone angle, maximum injection pressure), the piston combustion chamber shape, and the compression ratio are the same as the 1.6 L 88 kW specifications⁽⁸⁾. Therefore, like the previous EURO 5-compliant model, high-efficiency combustion was

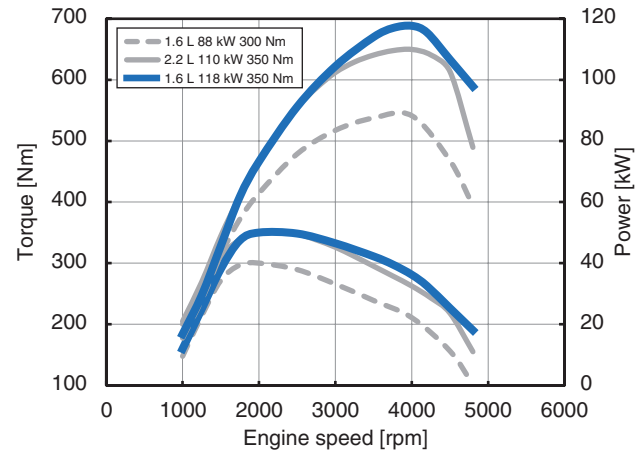


Fig. 9 Power and torque curve

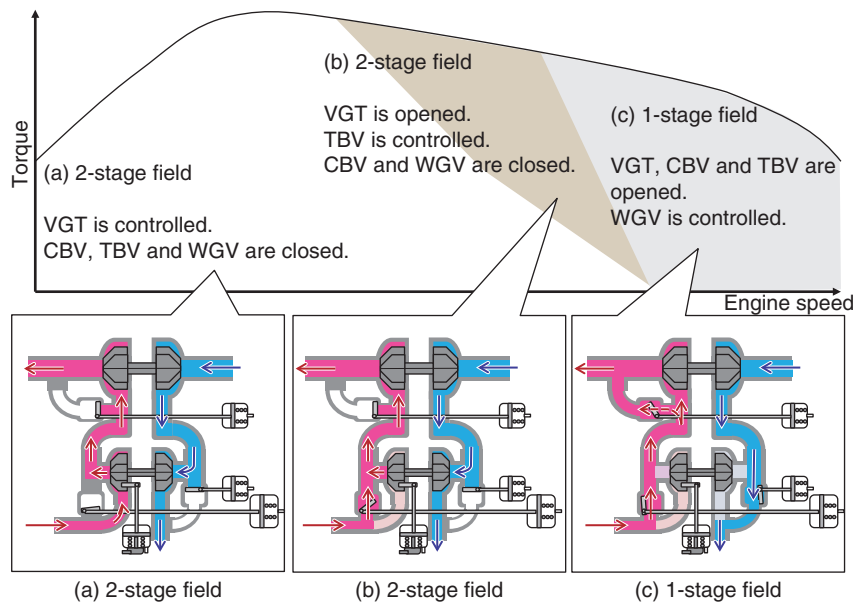


Fig. 8 Turbocharger operating strategy in engine map

obtained by LP-EGR, and the combustion settings secure a high degree of constant volume mainly for diffusive combustion that uses full-range 2-step pilot injection (PI) as the basic injection pattern^{(8), (9)}. The concept for complying with EURO 6 was to avoid an increase in pumping loss and drop in combustion efficiency due to high boost and high EGR, achieve low-fuel-consumption performance while maintaining the feed gas level at the EURO 5 standard⁽⁸⁾, and add an aftertreatment system.

However, there is the issue that a drop in exhaust temperature cannot be avoided as shown in Fig. 10, due to lower fuel consumption and an increased heat mass as a result of using a 2-stage turbocharger. Development of a new catalyst capable of adsorbing and storing NOx even at low temperatures is demanded to support a lower NOx storage catalyst (NSC) bed temperature due to this drop in exhaust temperature. In addition, conventional NSC do not have conversion performance capable of satisfying the EURO 6 NOx regulations, so the NOx conversion rate needs to be increased by 40 points or more compared to EURO 5, and the NOx conversion performance is necessary over a wide temperature range including high temperatures.

To address this issue, the catalyst adsorbent was changed from the zeolite used in the previous model to barium, and the optimum platinum group metal (PGM) carrier density was selected. By optimizing the catalyst surface structure and increasing the PGM amount compared to the previous catalyst, a lower conversion start temperature could be realized and the NOx was oxidized by the PGM, which increased the adsorptivity to the barium surface in the lean atmosphere from the cold condition. As a result, the NOx conversion rate could be further increased over a wide catalyst temperature range from low to high temperatures, and CO and HC conversion performance also increased as shown in Fig. 11.

3.4. Technology for Enhancing Fuel Economy

Technologies used to enhance the fuel economy of the newly developed engine can be broken down into reduction of mechanical friction, reduction of pumping loss using a

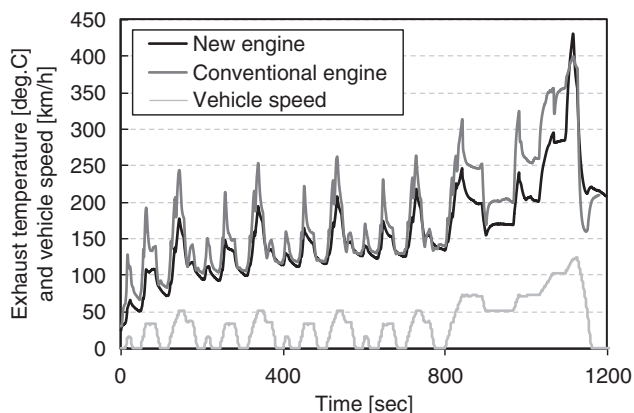


Fig. 10 Exhaust gas temperature in NEDC mode

2-stage turbocharger with a VGT-type HP turbocharger, and enhancement of combustion by applying after-injection.

The main goal of reducing mechanical friction is to reduce the sliding friction of reciprocating parts. This was accomplished by reducing the piston skirt area as shown in Fig. 12, applying a low-friction coating to the chain guide, and machining the cam journal to reduce the surface roughness and lower the sliding resistance. In addition, the shape of the balancer weight that was set as a part for increasing power was optimized as shown in Fig. 13 to reduce the resistance when the balancer agitates the surface of the oil accumulated in the oil pan. These technologies reduced the mechanical friction at 1500 rpm by 50% compared to the previous 2.2 L 110 kW engine⁽¹¹⁾⁻⁽¹³⁾.

The collision noise produced when the balancer drive chain and sprocket mesh is an issue when using specifications that achieve a driving speed-increasing ratio of 2x using only the chain. Therefore, the balancer shown in Fig. 14 that was applied to the new engine has specifications that reduce this collision noise and further enhance quietness by reducing the speed-increasing ratio of

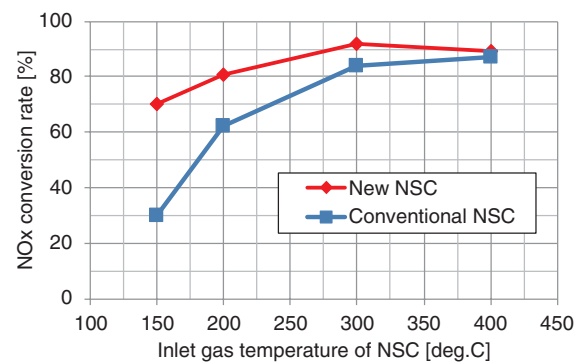


Fig. 11 NOx conversion rate of new NSC (test piece)

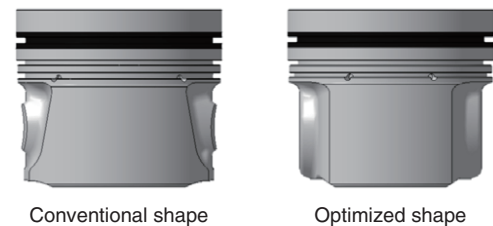


Fig. 12 Comparison of piston skirt area

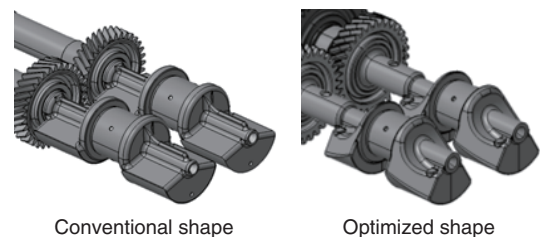


Fig. 13 Optimization of balancer weight shape

the chain to 1.3x and using a 1.5x speed-increasing gear to increase the speed to 2x.

Regarding combustion calibration, after-injection was used to reduce cooling loss and enhance the degree of constant volume in order to further increase the thermal efficiency compared to the 1.6 L 88 kW model. Figure 15 shows the rate of heat release at 1500 rpm, BMEP 645 kPa when after-injection is used. The main combustion fuel amount needed for the same required torque is reduced by the after-injection amount, so the rate of heat release during main combustion is suppressed, enabling reduction of the cooling loss from the combustion chamber and cylinder head wall surfaces. In addition, the ignition timing angle can be advanced without increasing the combustion noise produced by the main combustion, so the degree of constant volume increases, which contributes to reducing fuel consumption. As described above, the basic injection pattern is total 3-step injection that adds main injection (MI) to full-range 2-step PI. Combustion calibration used model-based calibration (MBC)⁽⁵⁾ to obtain fuel economy enhancement effects from after-injection. In addition, after-injection was additionally set only in the low-

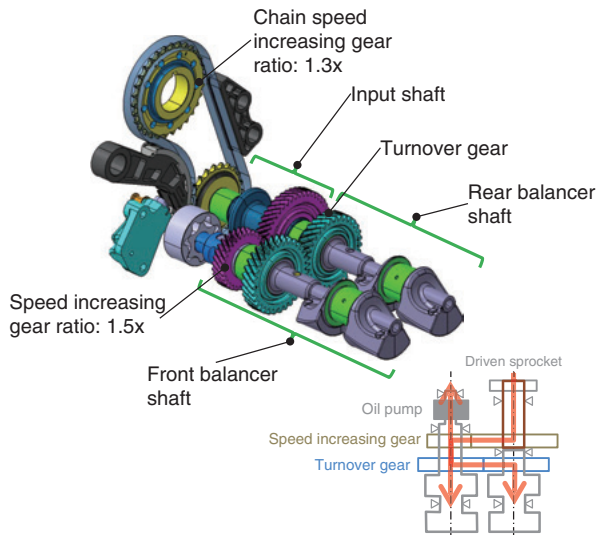


Fig. 14 Overview of balancer system

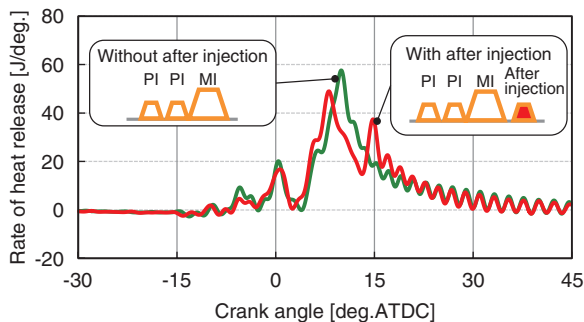


Fig. 15 Rate of heat release with after injection

medium-load range. These measures obtained fuel economy enhancement effects of 0.5% in NEDC mode.

In the standalone engine format, the technologies for reducing fuel consumption described above provided brake-specific fuel consumption (BSFC) enhancement effects (1500 rpm) as shown in Fig. 16 compared to the previous 2.2 L model.

3.5. Vehicle Power, Emissions and Fuel Economy Performance

Each technology described thus far related to increasing power, EURO 6 compliance and low fuel consumption was applied to the power unit mounted in the new CR-V for Europe released from 2015. Tests to compare the dynamic performance when mounted in a vehicle were performed by mounting the new engine and previous engines in CR-V and accelerating with the throttle fully open in third gear. Figure 17 shows these results. The new engine increased the absolute value of the maximum attained acceleration (peak G), which is one index of acceleration performance, by 7.5% and also shortened the time required to reach peak G, which is another index of acceleration performance. This enabled attainment of product appeal equivalent to not only the previous 1.6 L 88 kW specification model, but also running performance that allowed replacement of the 2.2 L model, which was the target.

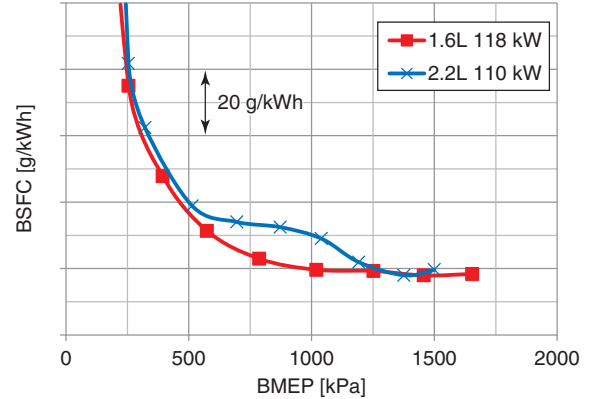


Fig. 16 Enhancement of BSFC from previous engine

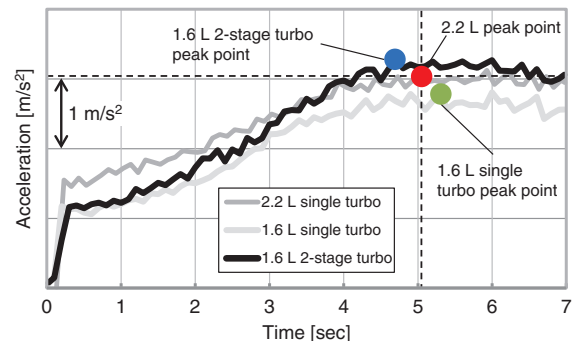


Fig. 17 Dynamic performance of 2-stage turbocharger

Figure 18 compares the engine output with that of competitors. The fuel consumption and engine power trend line for 4WD, MT specifications in the SUV segment shows that the new engine simultaneously achieved low fuel consumption and dynamic performance equivalent to the top class among competitors⁽¹¹⁾⁻⁽¹³⁾.

In addition, Fig. 19 (a) and (b) respectively show the

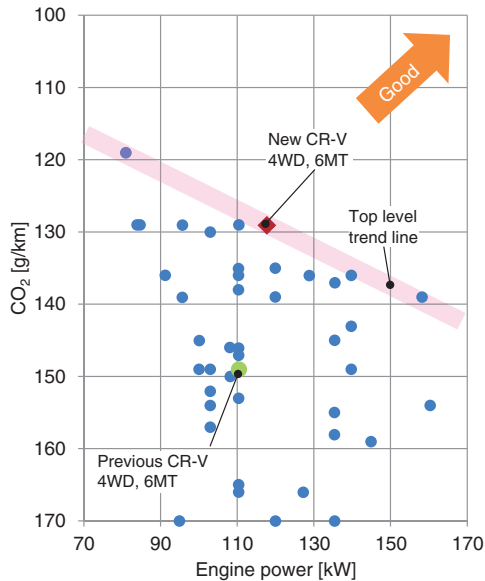


Fig. 18 Fuel consumption and engine power compared with competitors

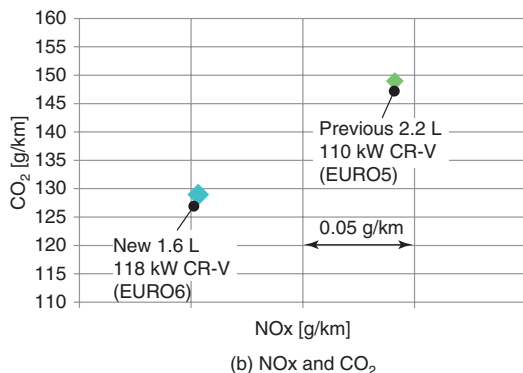
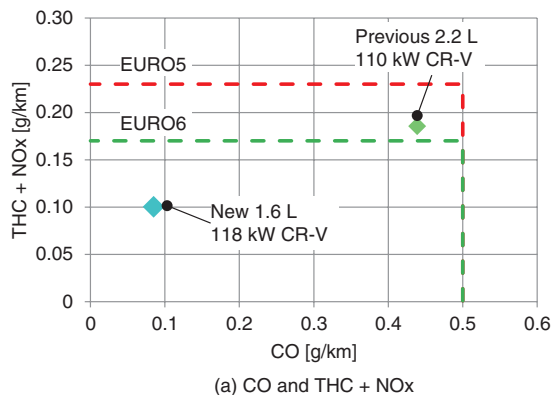


Fig. 19 Comparison of emissions with previous engine

achieved emissions and fuel economy values. The 2.2 L model complied with EURO 5 and had CO₂ emissions of 149 g/km, however the new engine complied with EURO 6, achieved CO₂ emissions of 129 g/km, and also increased fuel economy by 13.4%.

4. Conclusion

A high power, EURO 6-compliant 1.6 L diesel engine with low fuel consumption was developed by using a 2-stage turbocharger, representing a first for Honda. As a result of this development, the following technical results were obtained.

- (1) To achieve a high power output of 118 kW, a 2-stage turbocharger was used to gain the necessary high boost pressure. Only minimal changes were required to the engine architecture to support the increased in-cylinder pressure, keeping additional costs to a minimum.
- (2) A new NSC was developed that exhibits a high conversion rate from low to high temperatures, enabling compliance with EURO 6 emissions regulations while maintaining high combustion efficiency.
- (3) Boost pressure response and pumping loss were enhanced from the low-engine-speed range by applying the VGT system to the HP turbocharger of the 2-stage turbocharger. In addition, by reducing mechanical friction and enhancing combustion calibration, the new CR-V for Europe released in 2015 achieved fuel economy performance of CO₂ emissions of 129 g/km in NEDC mode, and simultaneously realized top-class fuel economy and dynamic performance.

References

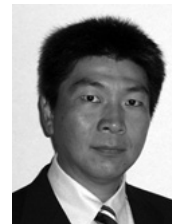
- (1) Abe, T., Matsui, R.: Development of New Turbocharged Common Rail Diesel Engine, JSAE Symposium Text, No. 10-04, p. 1-7, (2004)
- (2) Matsui, R., Shimoyama, K., Chiba, I., Hidaka, S., Nonaka, S.: Development of High-performance Diesel Engine Compliant with Euro-V, Honda R&D Technical Review, Vol. 20, No. 1, p. 20-26
- (3) Hidaka, S.: Development of a High-performance Diesel Engine Compliant with Euro 5, JSAE Forum Text, No.10 Forum-6, p. 31-41, (2010) (in Japanese)
- (4) Ikegami, N., Yamano, J., Ikoma, K., Matsui, R., Mori, S., Yano, T., Murata, Y.: Development of New 1.6L Diesel Engine, JSAE Symposium Text, No. 10-12, p. 24-30 (2013) (in Japanese)
- (5) Murata, Y., Tajiri, K., Sasaki, Y., Fukushima, H., Tsuda, M., Ueno, T., Koide, S.: Development of New 2.2L Fuel-Efficient Diesel Engine, JSAE Symposium Text, No. 15-11, p. 1-11 (2012) (in Japanese)
- (6) Murata, Y., Tajiri, K., Sasaki, Y., Fukushima, H., Ueno, T., Koide, S.: Development of the New 2.2L Fuel-Efficient Diesel Engine for Honda CIVIC, 21st Aachen Colloquium Automobile and Engine

- Technology, (2012)
- (7) Shuto, Y., Tachikawa, T., Emori, H., Ogino, K., Mori, S.: Development of New Generation 1.6L Diesel Engine (First Report), JSAE Annual Congress Proceedings, No. 63-13, p. 1-4 (2013) (in Japanese)
 - (8) Kabashima, T., Takasawa, S., Yoshida, Y., Matsui, K.: Development of New generation 1.6L Diesel Engine (Second Report), JSAE Annual Congress Proceedings, No. 6-13, p. 5-8 (2013) (in Japanese)
 - (9) Nishio, Y., Hasegawa, M., Tsutsumi, K., Goto, J., Iizuka N.: Development of New generation 1.6L Diesel Engine (Third Report), JSAE Annual Congress Proceedings, No. 5-13, p. 7-12 (2013) (in Japanese)
 - (10) Hoshino, S., Katsumata, K., Fukushima, H., Noto, T., Yasuda, J.: Development of New Generation 1.6L Diesel Engine (Fourth Report), JSAE Annual Congress Proceedings, No. 64-13, p.5-8 (2013) (in Japanese)
 - (11) Ishihara, Y., Murakami, O., Tabuchi, T., Sasaki, Y., Hatano, J., Fukushima, H., Aoyagi, S., Matsuo, Y.: Development of High Power and Low Emission 1.6L Diesel Engine, JSAE Annual Congress Proceedings, No. 131-14, p. 7-10 (2014) (in Japanese)
 - (12) Nishimori, K., Hatano, J., Ueda, K., Murakami, O., Imai, T., Fukushima, H., Matsuo, Y.: Development of 1.6L diesel engine with two stage turbocharger achieving Euro6 emission regulation, JSAE Symposium Text, No. 15-14, p. 52-57 (2015) (in Japanese)
 - (13) Matsuura, H., Ishihara, Y., Murakami, O., Tabuchi, T., Sasaki, Y., Hatano, J., Fukushima, H., Aoyagi, S., Matsuo, Y.: New Generation 1.6L Diesel Engine for the Honda CR-V, 36th International Vienna Motor Symposium, (2015)

■ Author ■



Junichi HATANO



Ken NISHIMORI



Hiroyuki FUKUSHIMA



Taro TABUCHI



Naoto KITAYAMA



Yoshinori ISHIHARA