

Turbocharged and Naturally Aspirated Gasoline Direct Injection V6 Engines with Common Architecture based on New Valve Train System

Shotaro TAKI¹

Satoshi KAWAWA¹

Kazumasa ISHII¹

Akio IMAKITA¹

Yukio KONISHI¹

Yuki TOMITANI¹

ABSTRACT

Two gasoline direct injection V6 engines were developed using a new valve train architecture with a common engine geometry: a turbocharged engine aimed at enhancing power performance, and a naturally aspirated engine aimed at enhancing environmental performance. Variable Timing Control for intake and exhaust was adopted to improve boost pressure responsivity for the turbocharged engine and thermal efficiency for the naturally aspirated engine. To maintain an engine size comparable to that of the previous engine, a new compact valve train was developed, combining a valve lifter-based Variable Cylinder Management system with built-in cylinder deactivation switching mechanism, hydraulic lash adjusters, and roller rocker arms. With these changes, these systems were equipped at the same cylinder head size as the previous SOHC engine. Furthermore, the new valve train allowed for a common engine geometry between the turbocharged and naturally aspirated engines, including cylinder head structure and rotational axis positions of the crank shaft and cam shafts, to help ensure commonality for the timing belt drive system and other systems. A single twin-scroll turbocharger was adopted for the turbocharged engine, achieving a maximum power of 265 kW and maximum torque of 480 Nm. The naturally aspirated engine features a fuel injection system with fuel pressure increased to 30 MPa, and a vehicle with the engine achieved an LEV III SULEV30 rating, producing PM of 1 mg/mile.

1. Introduction

In the North American market, there is a need for powertrains with driving force margin for SUVs and pickup trucks. In 1997, Honda developed a 3.0-L naturally aspirated (NA) SOHC VTEC V6 engine for increased power output. Then in 2003, to enhance environmental performance, Honda developed its Variable Cylinder Management (VCM) system⁽¹⁾, a rocker arm (R/A) based valve train with cylinder deactivation for switching between 6-cylinder and 3-cylinder operation. Next, looking to further enhance environmental performance in 2008, the company developed the VCM-II system for multi-stage switching between 6-cylinder, 4-cylinder, and 3-cylinder operation, pairing this VCM-II with an increased displacement engine for increased power in a modified NA 3.5-L V6 engine⁽²⁾. In 2013, a 3.5-L NA direct injection V6 engine⁽³⁾ was developed, combining VTEC, which switches valve lift to enhance power characteristics, with the VCM system for enhanced environmental performance.

This V6 engine is also used as the main powertrain for the Acura brand, which sells luxury vehicles mainly for

the North American market. In recent years, to increase the product appeal of its flagship high-performance models, Acura has seen demand for large power enhancements in the existing 3.5-L NA direct injection V6 engine. Forced induction with a turbocharger (T/C) is an effective means to increase power, although it comes with reduced launch response due to lag in boost pressure response in the low-rpm range. Boost pressure response can be improved with a twin-scrolling turbocharger to reduce exhaust interference and optimized control of valve overlap with Variable Timing Control (VTC) for intake and exhaust valves⁽⁴⁾.

Meanwhile, the Honda brand has demand in the North American market for a high displacement NA engine with a driving force margin for launching and smooth power characteristics from low to high rpm for SUVs and other vehicles used for hauling and towing. Also, demand for reduced environmental impact has increased in recent years across the automotive industry as a whole⁽⁵⁾. Thus, emissions performance at LEV III SULEV30 standards was targeted for the developed NA engine, which reduces nonmethane organic gas (NMOG) and NO_x to roughly a quarter of the LEV III ULEV125 standard achieved by the

¹ Honda Motor Co., Ltd.

E-mail: shotaro_taki@jp.honda

previous engine. Emissions performance can be enhanced by increasing fuel pressure in the fuel injection system and reducing fuel adhesion in the cylinder. Also, thermal efficiency can be improved with VTC for intake and exhaust to reduce pumping loss and optimized internal EGR volume.

Thus, it is desirable to adopt intake/exhaust VTC for the increased power and environmental performance. However, doing so requires a change in valve train architecture from the SOHC configuration of the previous engine to a DOHC configuration. Converting to DOHC and using the rocker arm-based VCM system means larger cylinder heads to support the valve train, making it non-trivial to maintain the same engine size as the previous engine. Therefore, a compact valve train was developed, combining a valve lifter-based VCM system adopting a built-in cylinder deactivation switching mechanism with hydraulic lash adjusters (HLAs) and roller rocker arms to help prevent an increase in engine size. Furthermore, this new valve train allowed for a common engine geometry between the turbocharged and NA engines, including cylinder head structure and rotational axis positions of the crank shaft and cam shafts. It also ensures commonality for the timing belt drive system.

This paper describes the newly developed valve train, along with the development aims and technologies applied for the two direct injection V6 gasoline engines using this valve train as a common structure (Fig. 1): the turbocharged model for enhanced power performance, and the NA model for enhanced environmental performance.

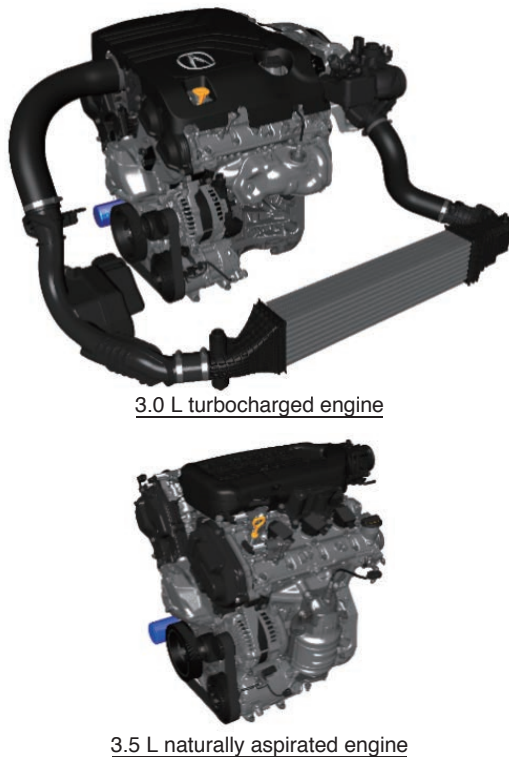


Fig. 1 Overview of newly developed engines

2. Development Targets

The development targets for the turbocharged and NA engines with the new valve train in common are as follows:

- (1) New valve train
 - Adopts intake/exhaust VTC and VCM system
 - Cylinder head size equivalent to the previous engine
 - Common engine geometry (valve train architecture, cylinder head structure, main rotational axis positions)
- (2) Turbocharged engine
 - Maximum power 265 kW, maximum torque 480 Nm (4.0–4.5-L NA engine equivalent)
 - Improved launch response
 - Maximum thermal efficiency of 36.5% or more
- (3) NA engine
 - Achieves LEV III SULEV30 category for emissions performance
 - Maximum thermal efficiency of 37.5% or more

3. New Valve Train

Figure 2 shows a comparison of valve train architectures for (a) the valve lifter-based VCM system for

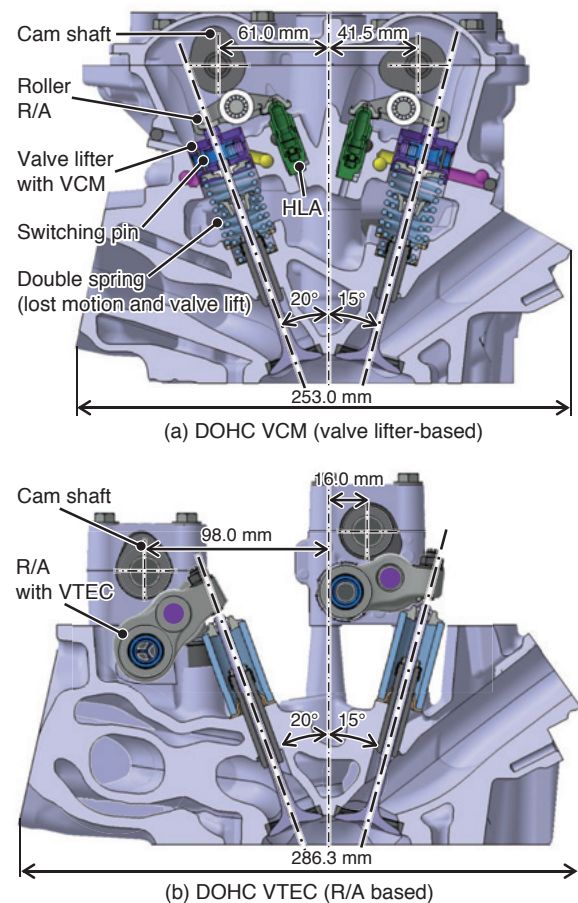


Fig. 2 Comparison of valve train architectures between previous and newly developed models

the developed DOHC architecture and (b) the rocker arm-based VTEC system as used in DOHC I4 engines.

The VCM system features cylinder deactivation switching pins built into the valve lifters and uses two valve springs with a retainer for each spring to consolidate the VCM system on the valve shaft together with the lost motion assembly. Also, using HLA and roller rocker arms allows the cam shafts to be positioned closer to the cylinder center than the valve shafts compared to the rocker arm-based DOHC VTEC architecture in Fig. 2(b). This prevents the adoption of a VCM system from enlarging the cylinder head size, while also achieving an equivalent valve angle.

The valve lifter-based VCM system has been newly developed for automobiles based on the Hyper VTEC valve control system with a valve deactivation mechanism for motorcycles⁽⁶⁾. Components for the system are shown in Fig. 3, and valve lifter motion during the cylinder deactivation switching operation is given in Fig. 4. Switching for cylinder deactivation is hydraulically controlled from oil galleries on the cylinder head with a switching pin built into the valve lifter. During valve lift activation, hydraulic pressure from the activation oil gallery pushes the switching pin against the stopper pin, and the valve is lifted via the switching pin. During valve lift deactivation, hydraulic pressure from the deactivation oil gallery slides the switching pin, aligning a through hole in the switching pin with the valve shaft. When the valve lifter is lifted, the valve stem end slides in the through hole and stops the valve lift. A slide retainer and outer spring that slide around the valve stem in the axial direction allow valve lifter motion to track with the cam profile.

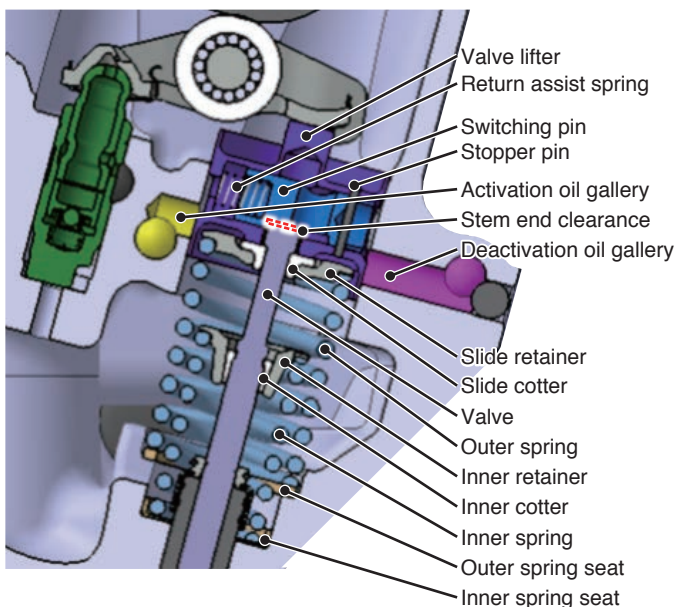


Fig. 3 Component of valve lifter-based VCM

The new valve train is the first Honda cylinder deactivation valve train to be combined with HLAs. By adopting HLAs, the clearances between rocker arm, cam lobe, and valve lifter as generated by tolerance variations in components can automatically be reduced to zero. This reduces cam profile and valve lift offsets, as well as variations in combustion performance due to reduced variations in the intake air flow rate, producing a maintenance-free valve train. In the VCM system with HLAs, the clearance required for activation of the cylinder deactivation switching pin was set between the switching pin and valve stem end to achieve reliable activation.

Figure 5 shows an overlay comparison of the cylinder head cross sections of the previous SOHC engine with VTEC-VCM system and the newly developed DOHC engine with VCM system. A cylinder head size equivalent to that of the previous engine was achieved while adopting the DOHC structure and VCM system. Also, by using an aluminum alloy cam cover with integrated cam journal, the cylinder head height including the cover was reduced by 30 mm from the previous engine.

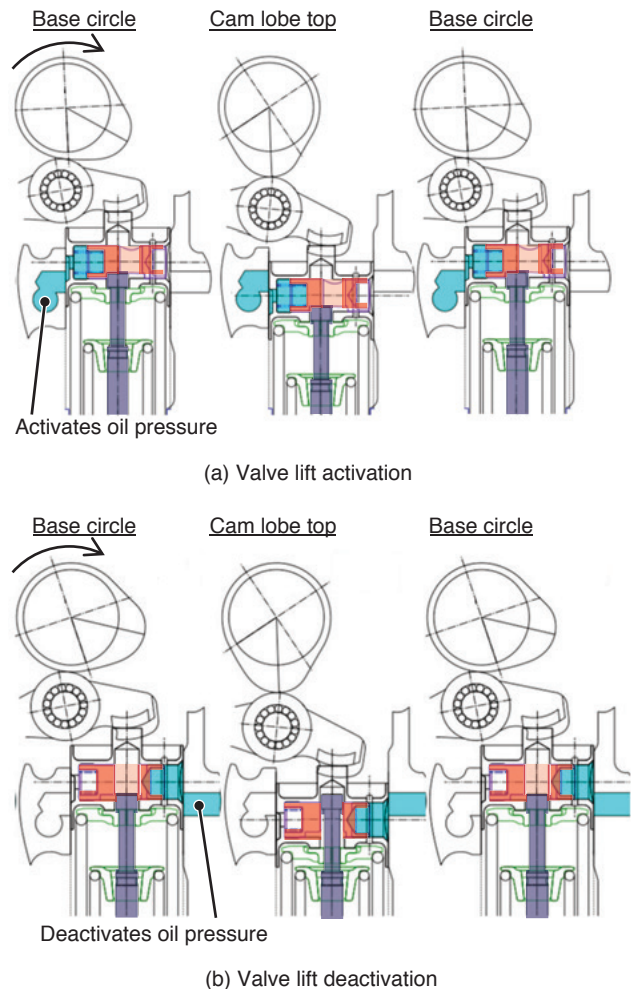


Fig. 4 Valve lifter motion

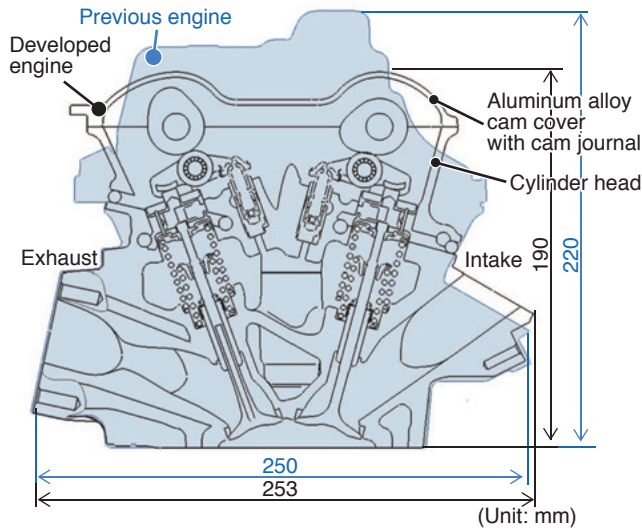


Fig. 5 Comparison of cylinder head appearances

4. Common Engine Geometry

In the developed engine, the new valve train allowed for a common engine geometry to be shared between the turbocharged and NA engines, including cylinder head structure and rotational axis positions of the crank shaft and cam shafts. Furthermore, the bore pitch, block height, bank angle, and other measurements were carried over from the previous engine. This allowed for an engine of the same size as the previous engine while adopting the DOHC architecture and intake/exhaust VTC.

With the common engine geometry, the same timing belt drive system could be shared for both turbocharged and NA engines. The timing belt system layout is shown in Fig. 6. In general, V engines employ timing chain

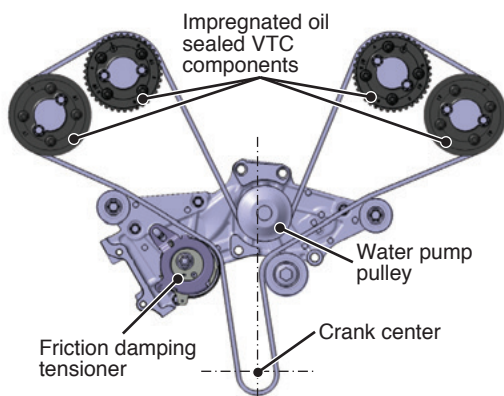


Fig. 6 Serpentine timing belt system

drive systems, which require multiple chains in a crank shaft driven system as each bank is offset. This enlarges the engine size in the crank shaft stroke direction. As with the previous engine, a serpentine layout was adopted to drive the crank shaft, cam shaft, and water pump with a single timing belt, preventing an increase in engine size.

The developed engines employ a DOHC structure and intake/exhaust VTC, which increases the amount of work driven by the valve train. Thus, to help ensure the strength of the timing belt, a friction damping tensioner was used in the auto-tensioning mechanism to reduce resonating tension.

The intake/exhaust VTC is integrated with the driven pulleys and driven by the timing belt. The structure of the driven pulleys with integrated VTC is shown in Fig. 7. As the pulleys are made of powder-sintered material, it is necessary to prevent oil seepage into the VTC from spoiling the timing belt. Therefore, O-rings were placed on the VTC component mating surfaces, and the powder-sintered pulleys were impregnated in resin to seal the oil and help prevent belt spoiling.

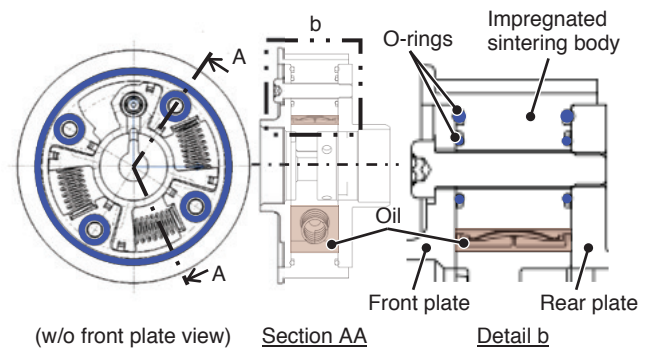


Fig. 7 Impregnation to seal oil for VTC

5. Turbocharged and NA Engine Specifications

Table 1 shows the main specifications of the turbocharged and NA engines with the new valve train in common as compared with the previous engine. By adopting a common structure between the turbocharged and NA engine models, the two new engines can be made with only minor changes, such as installing the turbocharger or increasing fuel injection system pressure. By adopting technologies suitable for each engine specification, the maximum power, maximum torque, and launch response were enhanced on the turbocharged engine, and emissions performance was increased on the NA engine.

Table 1 Comparison of engine specifications

	Previous NA engine	Developed NA engine	Developed T/C engine
Cylinder configuration	V6 cylinder	V6 cylinder	V6 cylinder
Displacement [cc]	3471	3471	2997
Compression ratio	11.5	11.5	9.8
Bore × Stroke [mm]	Φ89 × 93	Φ89 × 93	Φ86 × 86
Bore pitch [mm]	98	98	98
Block height [mm]	235	235	235
Bank angle [deg]	60	60	60
Valve train configuration	SOHC – 4-valve / cylinder	DOHC – 4-valve / cylinder	DOHC – 4-valve / cylinder
Variable valve control device	Intake/Exhaust VTEC and VCM	Intake/Exhaust VTC and VCM	Intake/Exhaust VTC and VCM
Variable cylinder management	6 – 3 cylinder switching	6 – 3 cylinder switching	6 – 3 cylinder switching
Cam drive system	Belt drive / Hydraulic tensioner	Belt drive / Friction damping tensioner	Belt drive / Friction damping tensioner
Aspiration system	Natural aspiration	Natural aspiration	Twin-scroll turbocharged aspiration
Fuel injection system	Direct injection	Direct injection	Direct injection
Maximum fuel pressure [MPa]	20	30	20
Fuel grade	RON91	RON91	RON95
Emission category	LEV III ULEV125	LEV III SULEV30	LEV III ULEV70
Maximum thermal efficiency [%]	36.5	37.5	36.5
Maximum power [kW/rpm]	209 / 6000	213 / 6100	265 / 5500
Maximum torque [Nm/rpm]	355 / 4700	355 / 5000	480 / 1400 - 5000

6. The Developed Turbocharged Engine

For the newly developed turbocharged engine, a single turbocharger was adopted to realize a compact layout, and the same engine length as the previous engine was achieved by mounting the turbocharger above the transmission (Fig. 8).

Using a single turbocharger to increase power means a larger turbocharger, making boost pressure response in the low-rpm range an issue. Thus, a twin-scroll turbocharger with lower exhaust interference was adopted to improve boost pressure response. Figure 9 shows a comparison of boost pressure response between twin-scroll and mono-scroll turbochargers. When changing load at a fixed engine speed of 1500 rpm, the twin-scroll turbocharger reached 80% of maximum torque 0.5 seconds faster than the mono-scroll turbocharger.

Combustion technology was carried over from the concept for the 2.0-L I4 turbo engine⁽⁴⁾, with thermal efficiency improved by suppressing knocking through rapid combustion with enhanced in-cylinder turbulent kinetic energy. Figure 10 shows the intake port, piston crown shape, and in-cylinder flow as calculated by CFD. The upright edge at the port bottom guides the mainstream of intake air to the upper surface of the intake valve and strengthens tumble flow, and the crown shape of a large-radius shallow dish enhances the retention of tumble flow.

An overview of the intake/exhaust VTC control strategy is shown in Fig. 11. In the low-rpm, high-load region, which dictates launch response, valve overlap was increased, and boost scavenging effects were used to increase torque (a). At low rpms and low to mid load, thermal efficiency was improved by optimizing internal

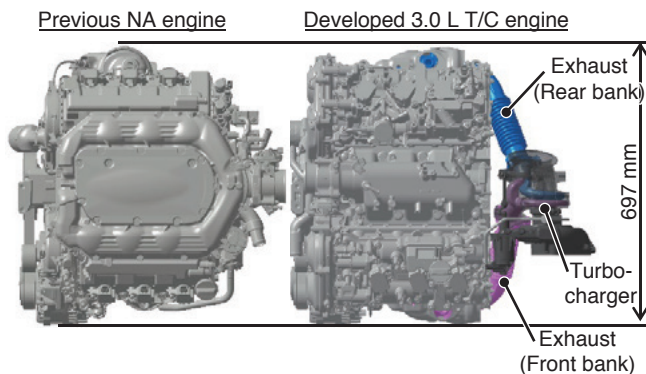


Fig. 8 Comparison of engine width between previous NA and developed T/C engines

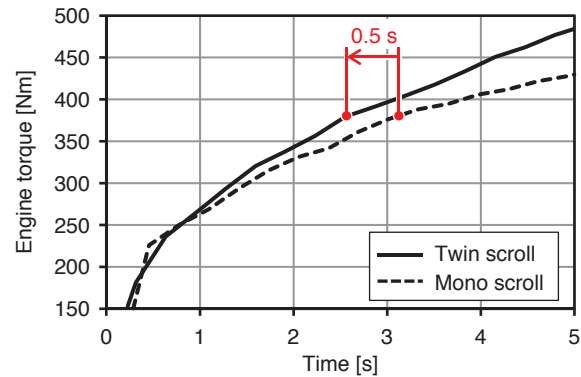


Fig. 9 Engine torque response at 1500 rpm

EGR volume, and fuel economy was improved with cylinder deactivation to reduce pumping loss (b, c). At mid to high rpms, the range was optimized to reduce valve overlap, and thermal efficiency was improved by enhancing exhaust efficiency to reduce knocking (d). In the engine start-up and idle range, valve overlap was reduced to reduce internal EGR volume and stabilize combustion (e).

Figure 12 shows the engine power and torque characteristics. Maximum power is 265 kW, and maximum torque is 480 Nm from 1400 rpm to 5000 rpm. Next, Fig. 13 shows a thermal efficiency map of the engine. The engine achieved a maximum thermal efficiency of 36.5%, and the area with a thermal efficiency of 34% or more was expanded while still enhancing power and torque.

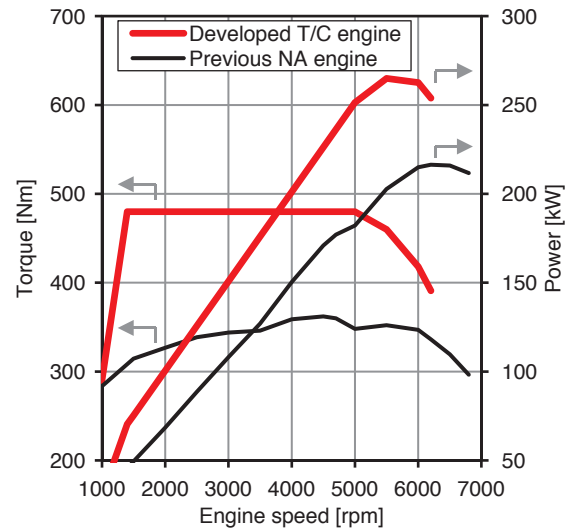
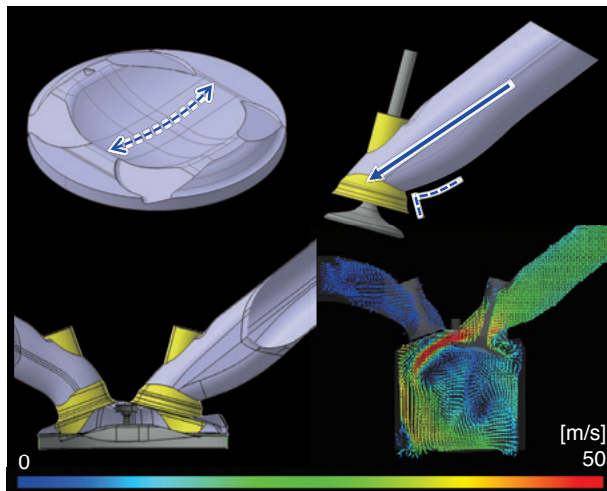


Fig. 12 Engine performance



(At 1500 rpm, wide open throttle (WOT), crank angle 470 deg)

Fig. 10 Intake-cylinder flow of T/C engine

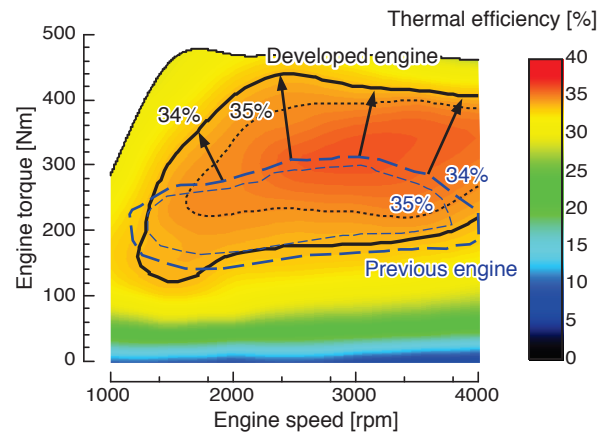


Fig. 13 Thermal efficiency map of developed T/C engine

7. The Developed NA Engine

For the developed NA engine, substantial reductions in unburned gas emissions and soot emissions were needed to achieve the LEV III SULEV30 regulation standards. Thus, the maximum fuel pressure for direct injection variable fuel pressure control was increased from 20 MPa in the previous engine to 30 MPa, and spray was atomized to reduce fuel adhesion in the cylinder. Also, the injector nozzle hole size was reduced while increasing fuel pressure to help ensure the same injection volume as the previous model, reducing the spray tip penetration (Fig. 14). Penetration was further reduced with multistage injection to reduce the continuous injection period (T_i).

Figure 15 shows the region in which multistage injection is applied. To help ensure stable combustion

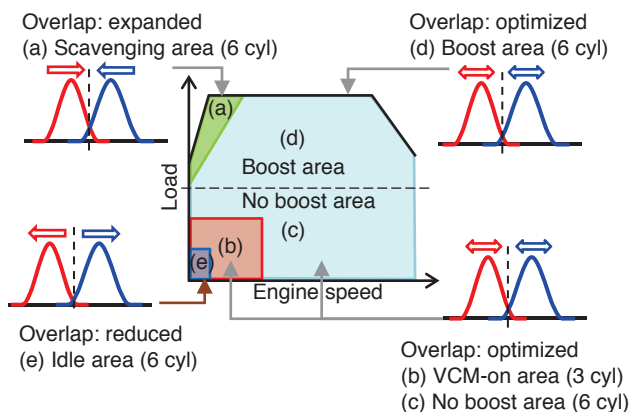


Fig. 11 Intake/Exhaust VTC control strategy

performance, the multistage injection conditions are changed for each driving condition. With these technologies, a vehicle with the NA engine achieved LEV III SULEV30 and PM of 1 mg/mile, enhancing emissions performance.

To improve thermal efficiency, the same as in the turbocharged engine, intake ports for increased tumble flow and a piston crown shape that maintains tumble flow were adopted to modify combustion by enhancing in-cylinder flow. Figure 16 shows the intake port, piston crown shape, and in-cylinder flow as calculated by CFD. The intake air flow rate was prevented from decreasing by using a larger sectional shape than the turbocharged engine, while enhancing flow with upright edges at the port bottom. In addition, the crown radius was designed to balance a high compression ratio with tumble retention.

An overview of the intake/exhaust VTC control

strategy is shown in Fig. 17. Valve overlap was optimized for all driving ranges. At low to mid rpms (a), thermal efficiency was increased by reducing pumping loss and optimizing internal EGR volume. By further combining with cylinder deactivation (b), thermal efficiency was increased for a wide range of driving conditions. At high rpms, the aim was to enhance knocking suppression through higher exhaust efficiency (c), and to increase power by optimizing valve overlap reductions.

Through these technologies, a maximum power of 213 kW and a maximum torque of 355 Nm were achieved, which are both at least as good as the previous engine. Finally, Fig. 18 shows the thermal efficiency map. Maximum thermal efficiency improved from 36.5% with the previous engine to 37.5%, and the area with a thermal efficiency of 35% or more was expanded.

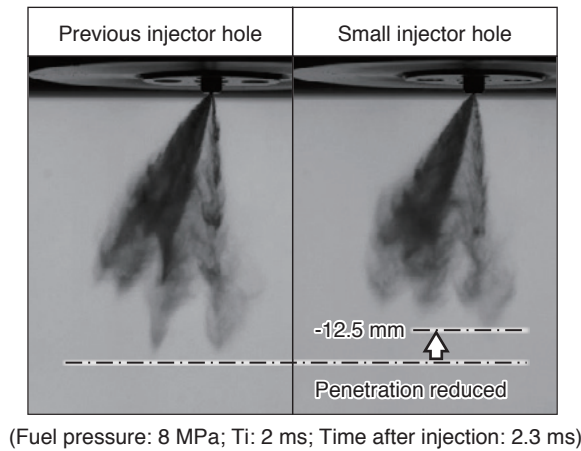


Fig. 14 Effect of small injector hole diameter

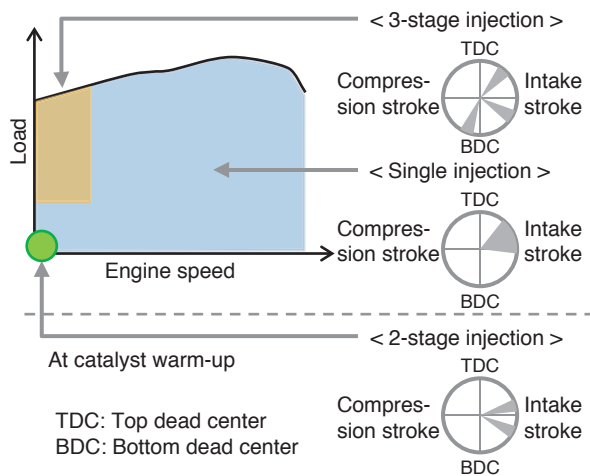


Fig. 15 Fuel injection operation

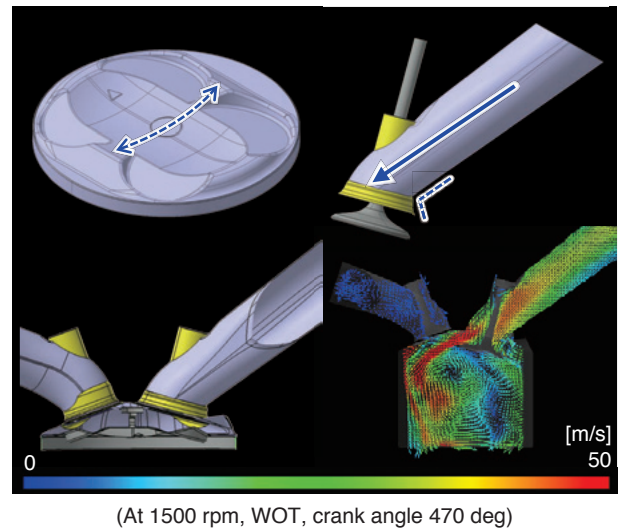


Fig. 16 In-cylinder flow of NA engine

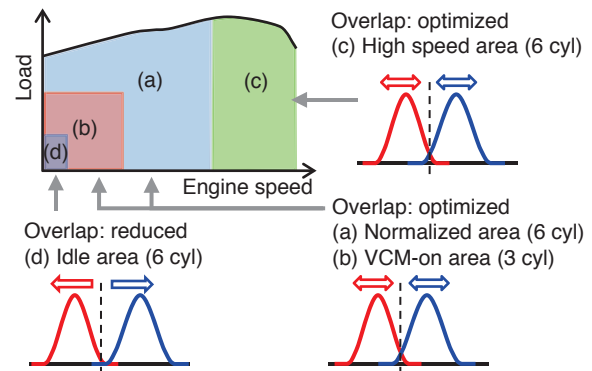


Fig. 17 Intake/Exhaust VTC control strategy

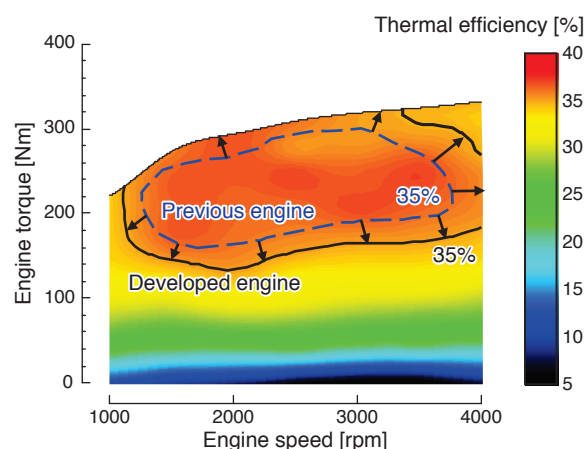


Fig. 18 Thermal efficiency map of developed NA engine

8. Conclusion

Turbocharged and NA direct injection V6 gasoline engines were developed with a new common valve train architecture, achieving the following results:

- (1) The new valve train has cylinder deactivation switching mechanisms built into the valve lifters, achieving a compact VCM system.
The engines combined this valve train with HLAs and roller rocker arms, also adopting DOHC and intake/exhaust VTC, and achieving a cylinder head size comparable to that of the previous engine.
Adopting HLAs both reduced variations in combustion performance due to reduced variations in the intake air flow rate and produced a maintenance-free valve train.
The engine geometry was made common between the turbocharged and NA engines, ensuring commonality for the timing belt drive system and other systems.
- (2) The turbocharged engine achieved a maximum power of 265 kW and maximum torque of 480 Nm, increasing power by 26.7% over the previous engine and torque by 35.2%. It achieved a maximum thermal efficiency of 36.5%.
- (3) The NA engine achieved a maximum power of 213 kW and maximum torque of 355 Nm. In terms of environmental performance, the maximum thermal efficiency improved from the previous engine's 36.5% to 37.5%. Also, a vehicle with the engine achieved LEV III SULEV30 and PM of 1 mg/mile.

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■ Author ■



Shotaro TAKI



Satoshi KAWAWA



Kazumasa ISHII



Akio IMAKITA



Yukio KONISHI



Yuki TOMITANI