The New Toyota 2.0-Liter Inline 4-Cylinder ESTEC D-4ST Engine

- Turbocharged Direct Injection Gasoline Engine -

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Summary

Toyota has developed a new 2.0-liter inline 4-cylinder engine called the ESTEC D-4ST, a downsized turbocharged gasoline direct injection engine with superior thermal efficient combustion. This engine features a combination of a cylinder head with an integrated 4 into 2 exhaust manifold and a twin-scroll turbocharger, and achieves high-speed combustion using a fan spray direct and port injection system and a high in-cylinder tumble ratio. The engine also adopts the Atkinson cycle using Toyota's new center-spooled VVT with mid-position lock system (VVT-iW), crankcase ventilation using an ejector under boosted conditions, and heat management systems. This engine is capable of both seamless and invigorating acceleration while also ensuring good fuel economy.

1 Introduction

Toyota Motor Corporation has developed a new 2.0-liter inline 4-cylinder engine called the ESTEC D-4ST to respond to a wide range of customer's needs all over the world. ESTEC is Toyota's next-generation engine technology and stands for "economy with superior thermal efficient combustion," while D-4ST shows that this is a downsized turbocharged gasoline direct injection engine. This is Toyota's first turbocharged gasoline engine for seven years and was released in July 2014 in the Japanese market. Toyota plans to subsequently launch the engine in Europe and the rest of the world.

Figure 1 shows the history of Toyota's turbocharged gasoline engines and in-house turbocharger manufacturing. Toyota's first turbocharged gasoline engine was the M-TEU, which was installed in the 6th generation Crown in 1980. Since then, Toyota developed a range of mass-produced turbocharged engines over the course of 27 years. During this period, in addition to turbocharged gasoline engines for mass-production vehicles, Toyota also developed turbocharged gasoline engines for motorsport applications, starting with Japanese Group C category vehicles in 1982. Toyota's notable successes in this period include several World Rally Championship (WRC) titles in the early 1990s. Furthermore, Toyota fabricated turbochargers for gasoline engines in-house up to 2007 starting with the 3T-GTEU engine in 1982, and has continued to develop and mass-produce turbochargers for diesel engines up to the present day. In addition to turbochargers, Toyota also has a long history of developing and mass-producing other technologies such as gasoline direct injection systems, variable valve timing (VVT), Atkinson cycle engines, and cylinder heads with integrated exhaust manifolds. As a result, Toyota has developed the capability to fabricate a range of fundamental engine components in-house.

These technologies have now been further evolved and integrated together to create the new 2.0-liter inline 4-cylinder ESTEC D-4ST engine. This engine is manufactured under the constantly evolving Toyota Production System (TPS).

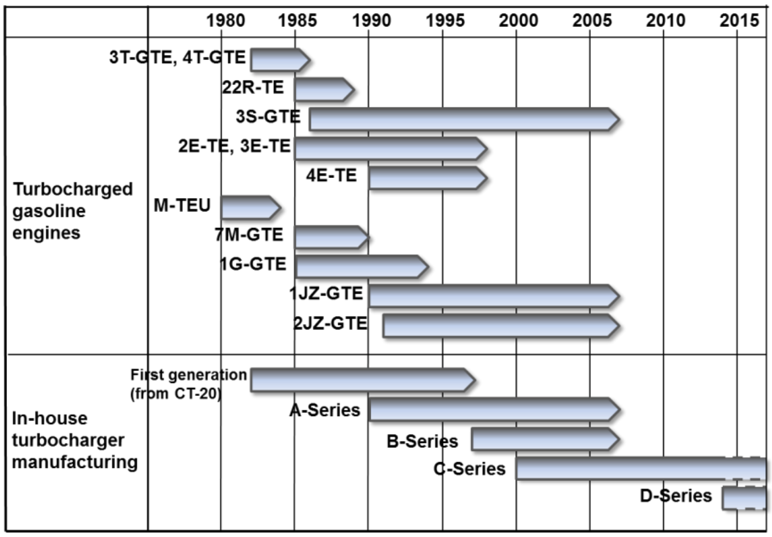

Fig. 1: History of Toyota’s Turbocharged Gasoline Engines and In-House Turbocharger Manufacturing

2 Engine Development Concepts

This engine was developed in accordance with the following seven concepts. The aim was to achieve suitable performance for a next-generation downsized turbocharged engine that would satisfy the needs of a wide range of customers, while ensuring that the engine could be produced around the world.

1. Quick response with a high and wide torque band from low engine speed ranges to achieve smooth acceleration
2. Environmentally friendly performance with low fuel consumption and emissions
3. Natural noise and vibration (NV) performance emulating a V6 engine
4. The same simple maintenance requirements as a naturally aspirated (NA) engine
5. A basic structure that facilitates future development
6. Applicability to both front-wheel drive (FWD) and rear-wheel drive (RWD) platforms
7. The capability to be produced on the same lines as the current AR-series NA engine, and compatibility with common global production facilities

The engine features the following technologies to achieve these concepts.

1) This engine combines a cylinder head with an integrated 4 into 2 exhaust manifold, twin-scroll turbocharger, and a compact directly mounted water-cooled intercooler. This combination achieves quick response by enhancing low-speed torque and high power, enlarges the stoichiometric air-fuel ratio (λ=1) operating region, and allows rapid warm-up of the exhaust system catalyst while reducing catalytic deterioration.

2) In addition to the high-speed combustion system (D-4ST) achieved through a fan spray direct and port injection system and a high in-cylinder tumble ratio, this engine also adopts the Atkinson cycle using a center-spooled VVT with mid-position lock system (VVT-iW). These technologies achieve class-leading fuel economy and power performance.

3) Measures were adopted to enhance fuel economy and power performance by reducing friction loss throughout the engine. These include a lightweight roller rocker valve system, a 3-stage oil pump, a timing chain with low sliding resistance, a chain guide manufactured using a material with low sliding friction, and a highly flexible V-ribbed belt.

4) A heat management system that promotes the warming up of coolant, lubricant, and sliding parts was adopted to provide an optimum heat transfer solution. Specifically, heat management is performed by a rapid warm-up system that reduces coolant flow to the cylinder block when the engine is cold, a dual chamber oil pan that reduces oil circulation to accelerate warm up, and an oil jet-controlled piston cooling system that cuts the supply of cooling oil to the pistons in accordance with the driving state to increase the temperature of sliding parts. In combination with the coolant temperature increase effect of the cylinder head with the integrated exhaust manifold, these technologies have a significant fuel economy improvement effect.

5) The development aimed to achieve an engine with lower levels of NV emulating a V6 engine. Class-leading NV performance was achieved by increasing the rigidity of the power plant, optimizing the balance of the balance shaft, and adopting plastic gears.

6) The world’s first crankcase ventilation system using an ejector under boosted conditions reduces engine oil deterioration and ensures the same oil maintenance interval as an NA engine even with the same mineral-based engine oils commonly used in NA engines.

7) The structural design approach was based on Toyota’s next-generation basic engine structure. For example, the structure of the cylinder head with the integrated exhaust manifold was designed to suppress the exhaust gas temperature and enable the catalyst to be installed closer to the engine in consideration of future trends in emissions standards. Furthermore, the structure of the camshaft housing was designed to be compatible with future changes to the valve train.

8) The engine was designed to be mounted in both FWD and RWD platforms while ensuring a common basic structure. Specific common components include the turbocharger, intake manifold, cylinder head cover, and camshaft housing. The FWD and RWD platform cylinder heads use the same castings and can be applied to either platform simply by adjusting a number of machining processes to alter the coolant flow inside the water jackets. The intercooler also shares the same design apart from the inlet shape.

9) Productivity was ensured by keeping the same bore pitch and key production requirements (such as the basic specifications and machining datums) as the current mass-produced NA AR engine series. The new engine can be produced on the same line as the AR engine series due to the adoption of an 8 sub-assembly structure (see Fig. 36 below for details). In the casting plan, the sizes of the major components were designed to be castable using Toyota's common simple and slim (S&S) dies on its production lines throughout the world.

Table 1 shows the main specifications of the engine and Fig. 2 shows the engine cross-section.

Displacement (cc)	1998
Bore x stroke (mm x mm)	ϕ86 x 86
Compression ratio	10 : 1
Fuel system	D-4S (DI + PFI)
Turbocharger	Twin-scroll turbocharger (Produced by Toyota in-house)
Intercooler	Water-cooled
Max. power (kW/rpm)	175/4800-5600
Max. torque (Nm/rpm)	350/1650-4000

Tab. 1: Engine Specifications

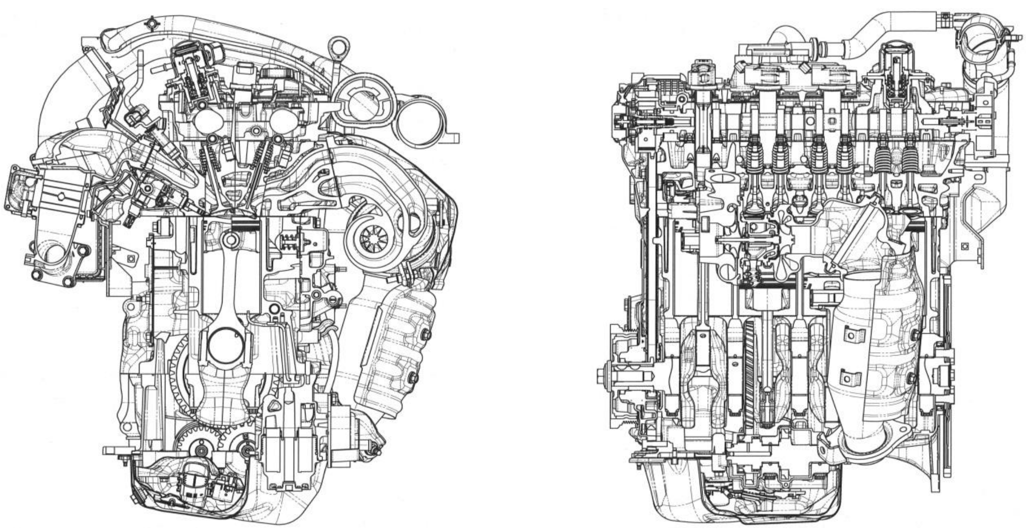

Fig. 2: Engine Cross-Section

3 Cylinder Head with Integrated 4 into 2 Exhaust Manifold, Twin-Scroll Turbocharger, and Compact Directly Mounted Water-Cooled Intercooler

One of the most important points in designing a turbocharged engine is the intake and exhaust system.

The key points for the exhaust system are how to efficiently direct the exhaust pulse energy to the turbocharger to facilitate the work of the turbocharger, and controlling the exhaust gas temperature within the optimum range from the standpoints of turbocharger reliability, catalyst activation, and catalyst reliability. In contrast, the key points for the intake system are the thorough reduction of intake system volume to improve response, reducing the pressure loss upstream of the turbocharger to ensure that the intake temperature is lowered stably, ensuring the cooling performance of the intercooler, and thoroughly avoiding adiabatic compression when supercharged air is forced into the cylinder after being sufficiently cooled by the intercooler. These aims were achieved by adopting a cylinder head with an integrated 4 into 2 exhaust manifold, twin-scroll turbocharger and compact directly mounted water-cooled intercooler, and designing an intake manifold with a low-volume surge tank and short branches.

The cylinder head with an integrated 4 into 2 exhaust manifold separates the exhaust ports into those for the number 1 and 4 cylinders and those for the number 2 and 3 cylinders. This reduces the exhaust pulse interference of neighboring cylinders in the combustion cycle, optimizes the cooling effect of the water jackets inside the cylinder head by tuning the length, diameter, and curvature of the exhaust ports, and allows the exhaust gas temperature to be controlled within the target range. This design optimizes the performance of the twin-scroll turbocharger. This design approach improves low-speed torque and boost pressure response (i.e., acceleration feel when the accelerator pedal is depressed), and also improves power performance (Fig. 5). Furthermore, reducing the exhaust gas temperature helps to enhance the reliability of the turbocharger, downstream catalyst, and other exhaust system parts. It also enlarges the λ=1 operating region. The areas around the exhaust ports are cooled by the water jackets and drilled passage, ensuring sufficient durability against thermal fatigue.

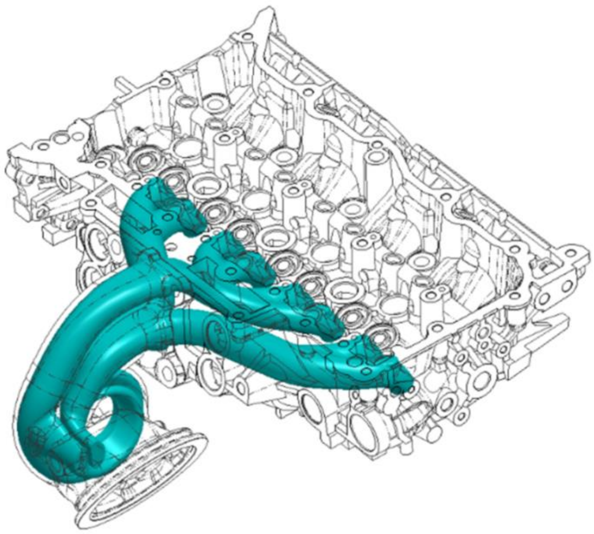

Fig. 3: Combination of Cylinder Head with Integrated 4 into 2 Exhaust Manifold and Twin-Scroll Turbocharger

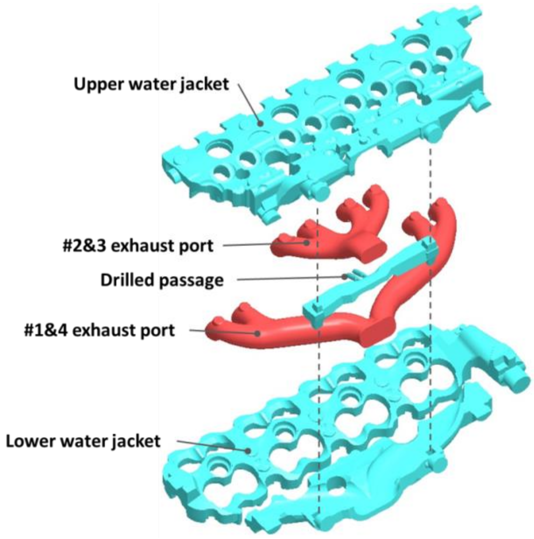

Fig. 4: Exhaust Ports and Water Jackets

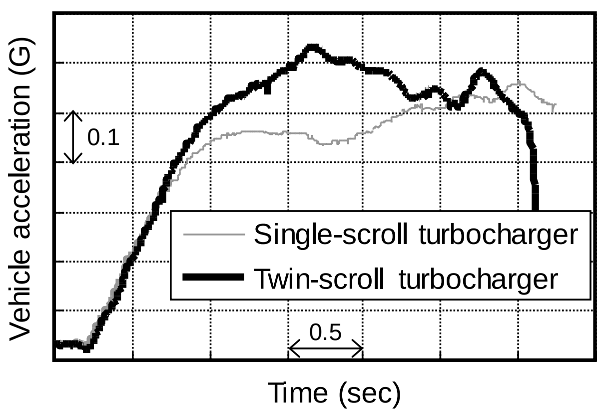

Fig. 5: Acceleration Improvement with Twin-Scroll Turbocharger

The turbocharger is directly mounted to the cylinder head with the integrated exhaust manifold. This is a new D-series turbocharger (Fig. 6) developed and manufactured in-house by Toyota to achieve the engine concepts described above. The design of the D-series turbocharger is radically different from the previous C series and features Toyota’s latest technologies as follows.

The turbine side uses a lightweight twin-scroll turbine housing with an inlet designed to guide the exhaust gas smoothly from the cylinder head with the integrated exhaust manifold to ensure sufficient extremely low speed torque (i.e., low-end torque) and transient response performance. The sizes of the turbine housing and blades were designed to ensure sufficient engine demand torque even under back pressure conditions that satisfy both low exhaust sound and emissions standards. As a result, the whole vehicle exhaust system was optimized. The twin-scroll turbine housing makes effective use of the exhaust gas pulsation pressure to help enhance boost pressure and torque from low engine speeds. The shape and size of the blades for both the turbine and compressor were optimized by computational fluid dynamics (CFD) and by evaluations of actual parts to ensure high efficiency over a wide range of low to high turbine speeds. The efficiency of the compressor in particular was significantly increased compared to the previous component by detailed attention to the aerodynamic design of the impeller. In addition, an active wastegate system was adopted that freely controls the opening degree of the wastegate valve for pumping loss reduction and fuel economy improvement.

Emissions were addressed by reducing the surface area of all exhaust system parts and guiding the exhaust gas directly to the catalytic converter by opening the wastegate valve on engine start (Fig. 7). These measures improve the warm-up performance of the catalyst.

Whirl vibration was reduced by semi-floating bearings and optimizing the bearing clearance. Combined with high-precision rotating balancing technology, this helps to enable low noise operation.

Reliability was ensured by thoroughly identifying phenomena through visualization techniques and durability limit tests. For the turbine housing, this included measurement of the operational distortion and analysis of the thermal stress together with the catalytic converter (Fig. 8). As a result, it was possible to optimize the shape and thickness distribution of each part by balancing the overall rigidity and thermal deformation of the exhaust system.

The development also actively focused on materials and production technologies. The new turbine housing material has a lower nickel (Ni) content than the conventional material while maintaining the same heat resistance. Before machining, the impeller uses an integrated hot forging line, which reduces the machining allowance and increases strength. In addition, new manufacturing process technologies, such as a cold-forged wastegate valve (Fig. 9) greatly reduced costs compared to the previous manufacturing method.

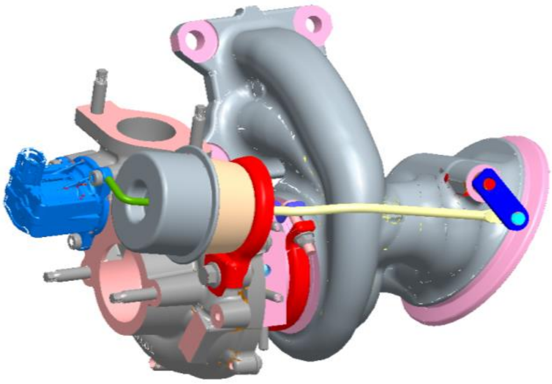

Fig. 6: Turbocharger

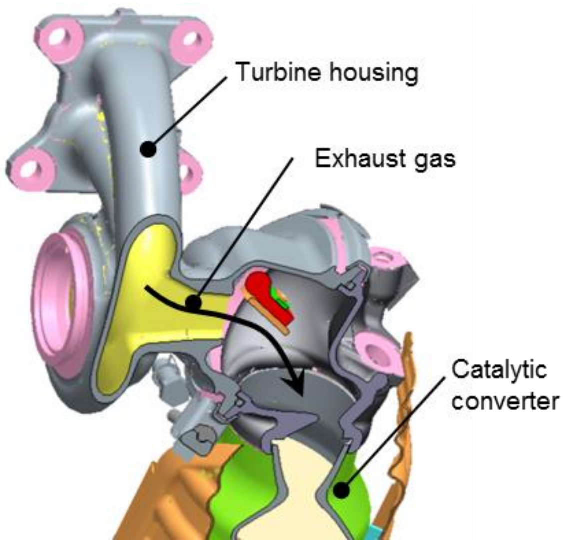

Fig. 7: Gas Flow from Scroll to Catalytic Converter

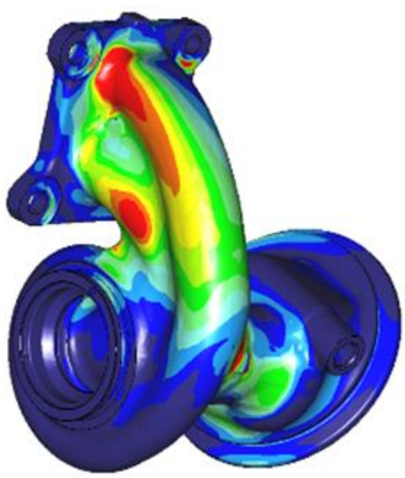

Fig. 8: Result of Thermal Stress Analysis

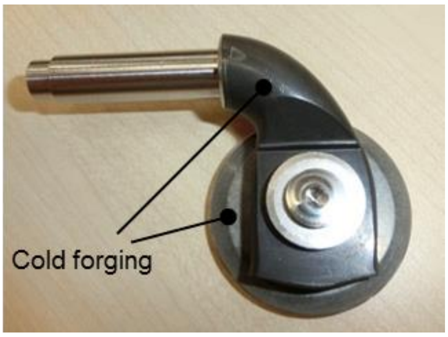

Fig. 9: Wastegate Valve

The intercooler system has a compact water-cooled design that minimizes the volume of the intake system downstream of the turbocharger, and is mounted immediately before the intake manifold (Fig. 10). The intercooler uses an independent low-temperature cooling circuit and electric water pump to maintain the optimum cooling effect in accordance with the driving state, regardless of the thermal load on the engine (Fig. 11). The internal design of the intercooler was revised to boost cooling efficiency by providing inner fins on the water passage side and optimizing the shapes of the fins and tubes on the supercharged air side. For the intake manifold, the volume of the surge tank was reduced to improve response, and knocking resistance was improved by suppressing the increase in temperature at the end of the compression stroke. This was accomplished by shortening the length of the intake manifold to reduce the forcing effect of the intake due to the inertia of the supercharged air after the intercooler. Adopting a plastic intake manifold also helps to reduce the heat transfer from the ambient temperature of the engine compartment. In addition, differences in the intake air volume between cylinders were minimized by analyzing the flows inside the intake manifold and the intake ports of the cylinder head.

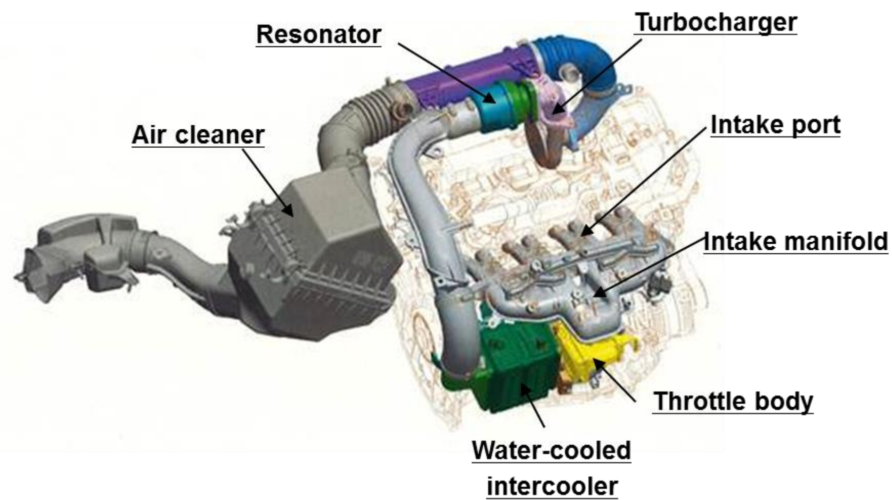

Fig. 10: Compact Intake System

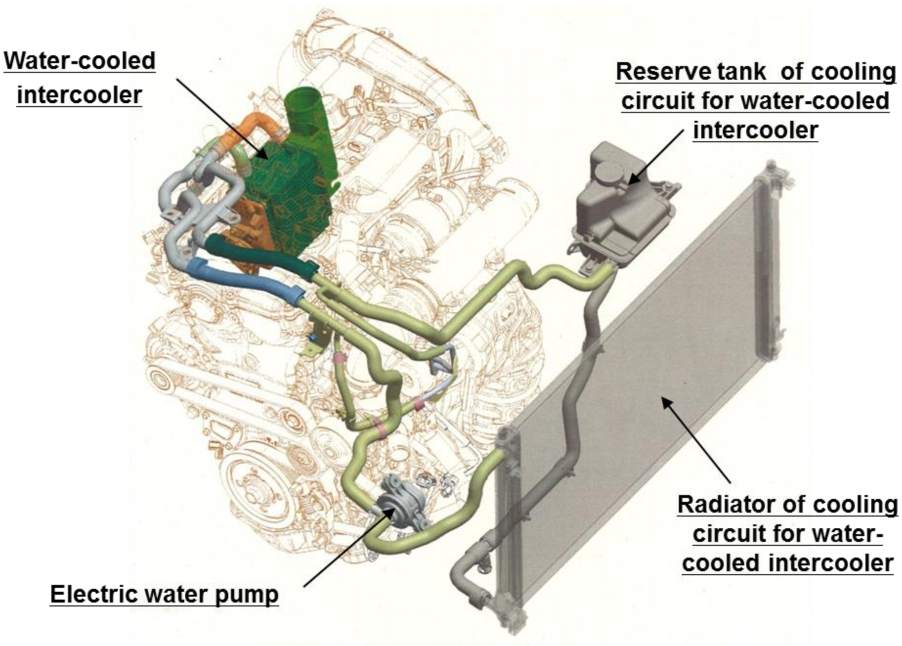

Fig. 11: Low-Temperature Circuit for Intercooler

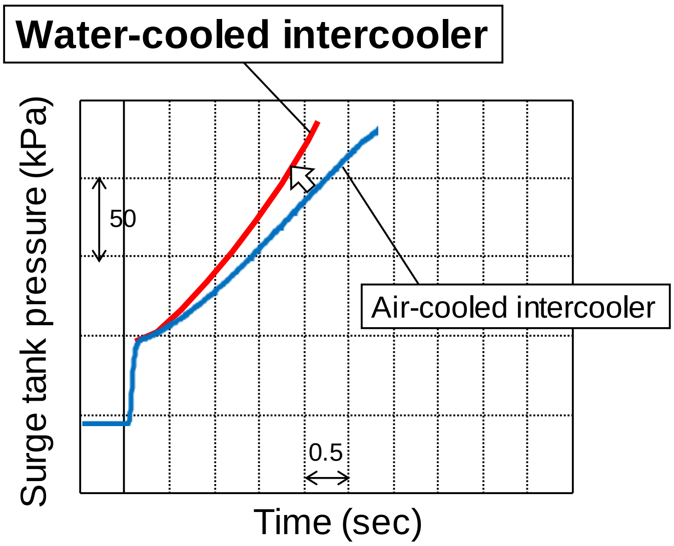

Fig. 12: Improvement in Boost Pressure Response with Water-Cooled Intercooler

4 High-Speed Combustion System (D-4ST) Derived from Fan Spray Direct and Port Injection System and High In-Cylinder Tumble Ratio

The combustion system is another important point in the design of a turbocharged engine. The new engine uses a boosted high-speed combustion system called D-4ST, which combines Toyota's original fan spray direct and port fuel injection system with a high in-cylinder tumble ratio.

Setting the compression ratio as high as possible is desirable to improve fuel economy. However, under boosted conditions, there is a greater volume of air in the cylinder and the temperature at the end of the compression stroke increases. As a result, the engine becomes susceptible to knocking. In addition to measures for the direct injection system, the shape of the intake ports was greatly modified from the base NA engine shape (Fig. 13) to resolve this issue and improve knocking resistance performance. The new port shape enables a high tumble ratio of 2.4 (Fig. 14). The design of the combustion chambers was also addressed to enable both stratified combustion for achieving rapid catalyst warm-up and normal homogenous mixture combustion. A lip was provided on the top of the pistons to form the stratified mixture and the top shape was designed to maintain the tumble ratio inside the cylinder. The lip position, height, and angle of the top shape were optimized by CAE and verified with actual parts to determine the final specifications (Fig. 15). In addition to measures to achieve high-speed combustion, knocking resistance was also improved by enhancing cooling performance. For example, drilled passages were added between the bores of the cylinder block.

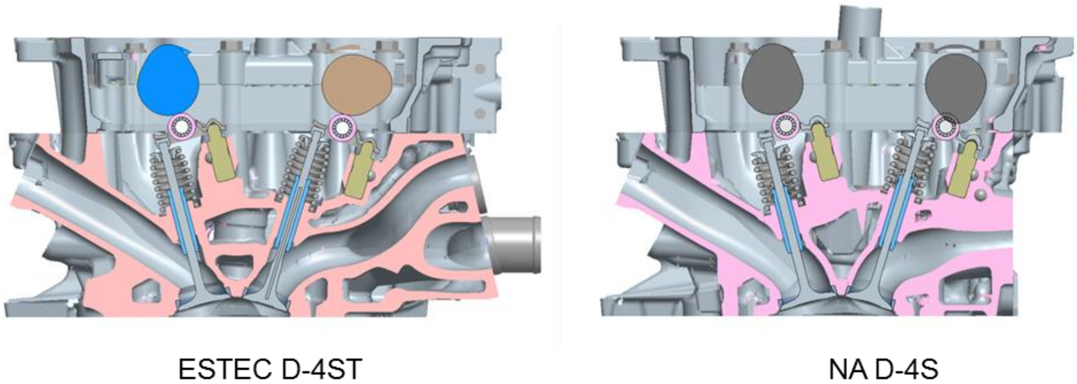

Fig. 13: Intake Port Cross-Section Comparison

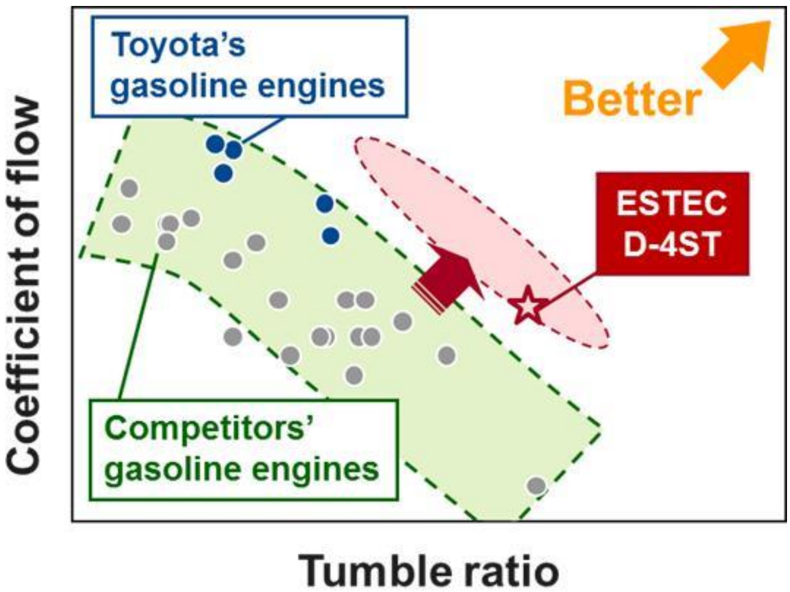

Fig. 14: Port Performance (Tumble Ratio × Coefficient of Flow)

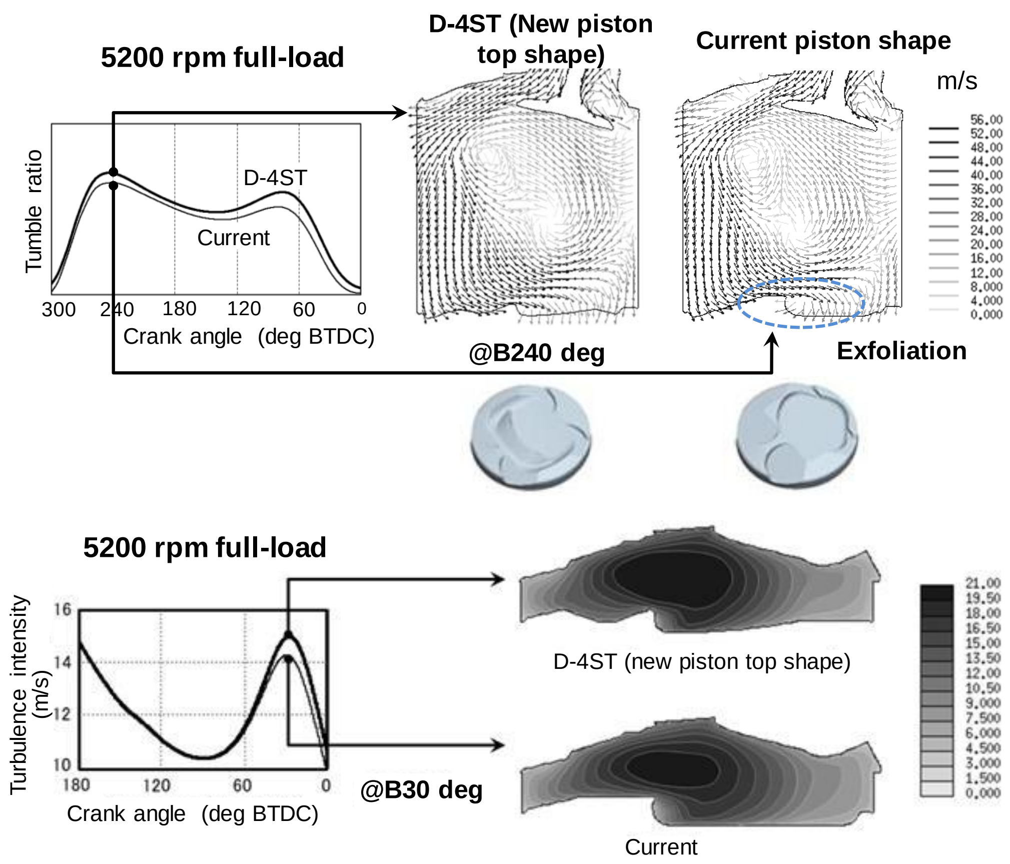

Fig. 15: Piston Top Shape and In-Cylinder Flow

The D-4S system that combines fan spray direct and port fuel injection was adapted for a turbocharged engine. Under boosted conditions, only direct injection is carried out. Based on the engine operating region, combustion efficiency is improved by carrying out one to three injections per cycle. Under non-boosted conditions, optimum combustion is achieved by port injection alone or a combination of both direct and port injection, in accordance with the engine operating region (Fig. 16). In addition, under cold conditions, the injection control takes full advantage of the merits of port injection, considering fuel dilution in engine oil.

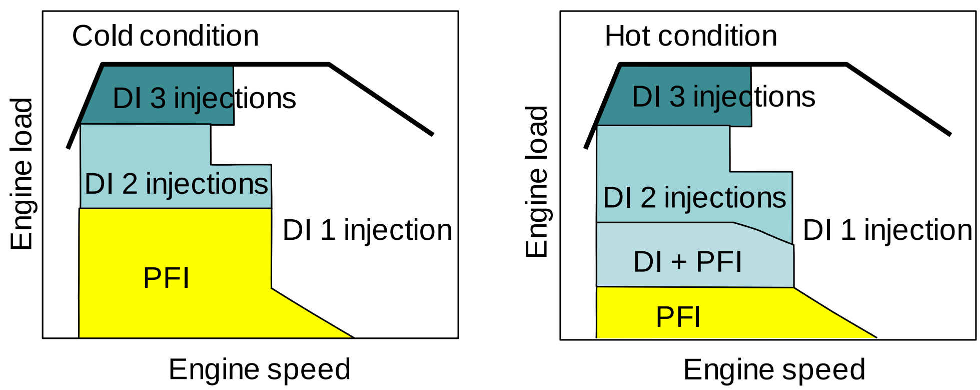

Fig. 16: Injection Strategy

5 Atkinson Cycle Using Center-Spooled VVT with Mid-Position Lock System (VVT-iW)

Toyota already uses the Atkinson cycle in hybrid system engines to reduce pumping loss and improve fuel economy by retarding the closing of the intake valve under light engine load operation. However, the Atkinson cycle has not been adopted in conventional engines equipped with a starter and a hydraulically driven VVT from the standpoint of ensuring startability under cold conditions.

Instead of the conventional hydraulic VVT, the developed engine adopts a VVT with an expanded variable valve timing range on the intake side (Fig. 17). This VVT is equipped with a lock function for the mid position that is used on engine start. Enabling the Atkinson cycle in this way improves fuel economy under light loads while ensuring engine cold startability. Under irregular driving conditions, such as the ignition being switched off while driving, engine cold startability is ensured by adding a mechanism that recovers the lock state during cranking for the next start, even if the VVT could not be locked in the mid position when the engine was stopped.

The oil control valve used for the VVT control features an additional dedicated oil passage to control the lock pin, in addition to VVT phase control. Five control modes enable lock operation in the mid position. The oil control valve also uses a center-spooled design that is integrated with the VVT. This reduces pressure loss in the oil passage and increases the VVT operation speed (Fig. 18).

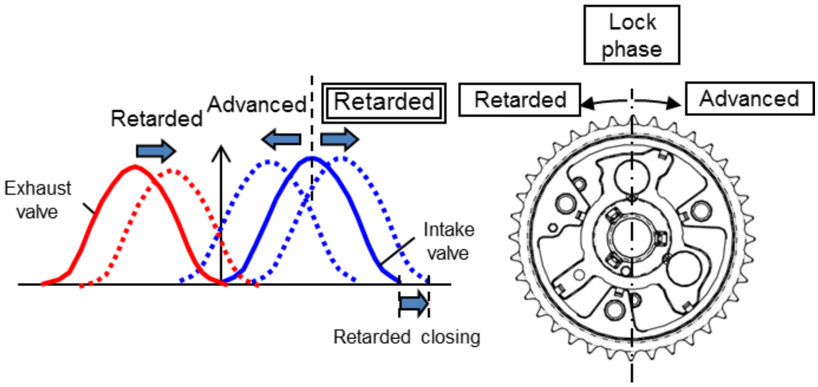

Fig. 17: VVT-iW System

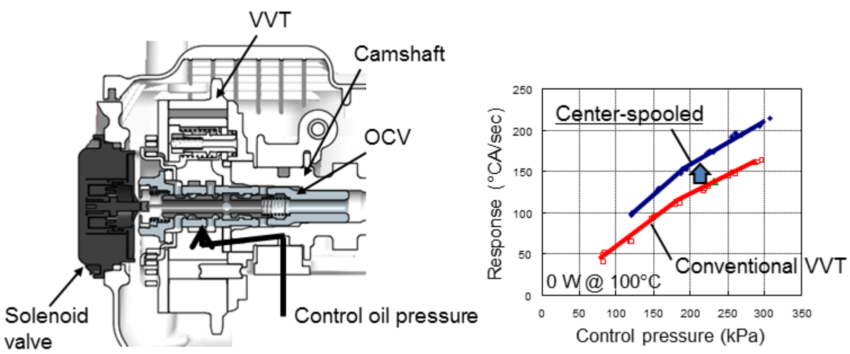

Fig. 18: Control Oil Passage and Operation Speed of Center-Spooled Oil Control Valve

6 Heat Management System

A new heat management system was adopted to improve the fuel economy of the warming up process. In consideration of the advantages and disadvantages of heat retention and transfer, the system design emphasized the retention of heat with as little heat transfer as possible from components that are heated by combustion (such as around the cylinder bore) and components in which heat is generated by sliding between parts (lubricated parts). In addition, the design aimed to efficiently transfer heat from non-sliding parts to sliding parts. Based on this strategy, a heat management system was adopted with the following components: a cylinder block heat retention system that reduces the coolant flow to the cylinder block under cold conditions, a system that stops the supply of cooling oil to the pistons and limits excess cooling of the pistons and piston rings in accordance with the driving state to reduce sliding friction with the bore, and a dual chamber oil pan that speeds up the increase in oil temperature by limiting the oil circulation to reduce the heat capacity and decrease wasted heat transfer. In addition, the cylinder head with the integrated exhaust manifold also functions to recover exhaust heat, which helps to improve fuel economy by speeding up the increase in coolant temperature and supporting the warm-up of parts such as the cylinder bores.

Figure 19 shows the system that promotes the warming up of the cylinder block. In addition to the thermostat at the coolant inlet of the cylinder block that controls the flow of coolant to the radiator during a conventional warm-up process, this system also includes a block thermostat that controls the volume of coolant guided to the cylinder block. The block thermostat cools the combustion chamber and improves knocking resistance by not reducing coolant flow to the cylinder head, thereby helping to maintain the fuel economy effect of advancing the ignition timing. At the same time, the block thermostat also improves fuel economy by reducing the coolant flow to the cylinder block to promote the increase in cylinder bore temperature. However, if the cylinder block coolant is completely shut off, the clearance between the pistons and cylinder bores in the warm-up process becomes too large, which worsens piston slap. Therefore, if lower noise and fuel economy can be achieved at the same time, optimizing the coolant flow volume can have a major positive impact on fuel economy. The block thermostat has a lower temperature opening setting than the main thermostat.

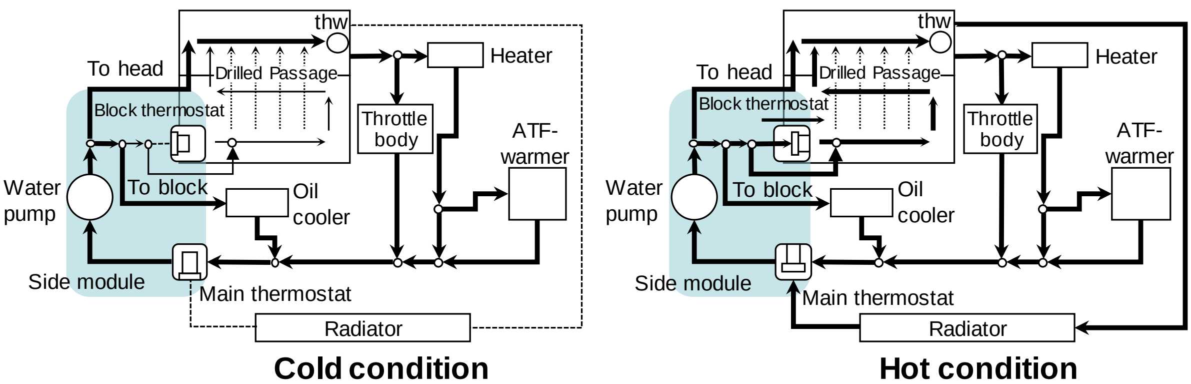

Fig. 19: System to Promote Cylinder Bore Warming Up

Figure 20 shows the system that stops the piston cooling oil jets. The system is provided with an electronically controlled oil switching valve and performs control based on a three-dimensional switching map for each engine coolant temperature, which is set in accordance with engine speed and load (Fig. 21). Stopping the oil jets under cold conditions improves the warm-up performance of the pistons and piston rings. Consequently, the reduced sliding friction with the cylinder bore also helps to improve fuel economy. This measure also reduces dilution of the engine oil by fuel under cold start conditions. Under hot conditions, the oil jets are stopped if the engine load is light to reduce the generation of deposits that accumulate on the piston top (Fig. 22). Reducing these deposits also helps to suppress low speed pre-ignition (LSPI), as described below.

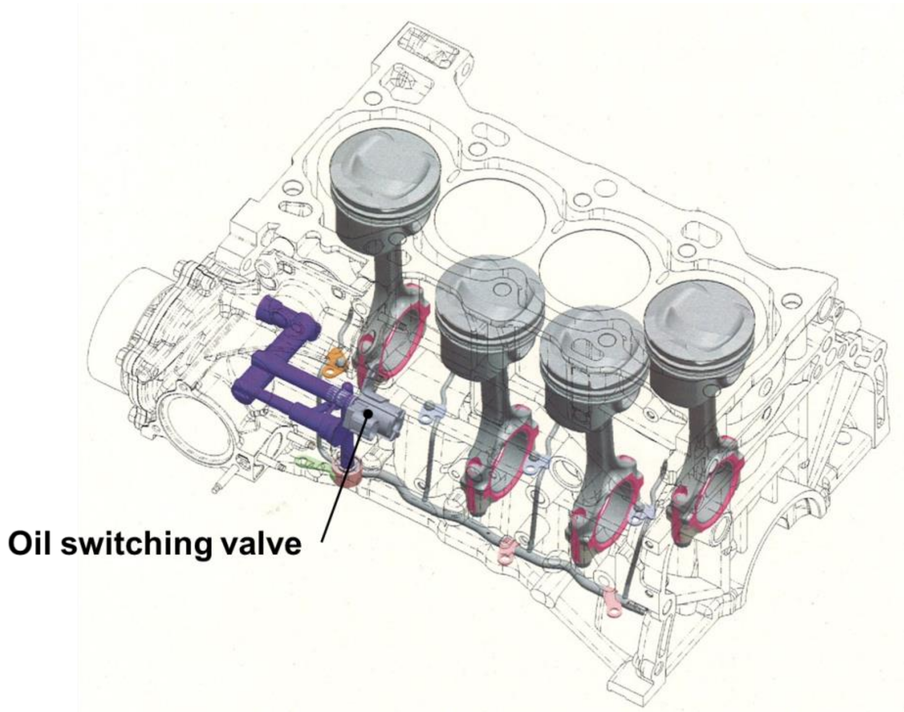

Fig. 20: System to Stop Piston Cooling Oil Jets

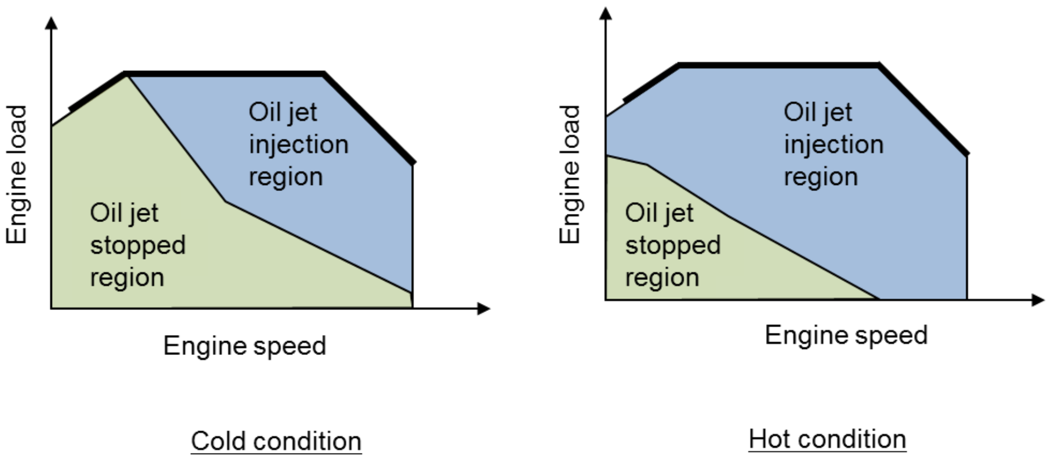

Fig. 21: Examples of Oil Jet Stopping Map

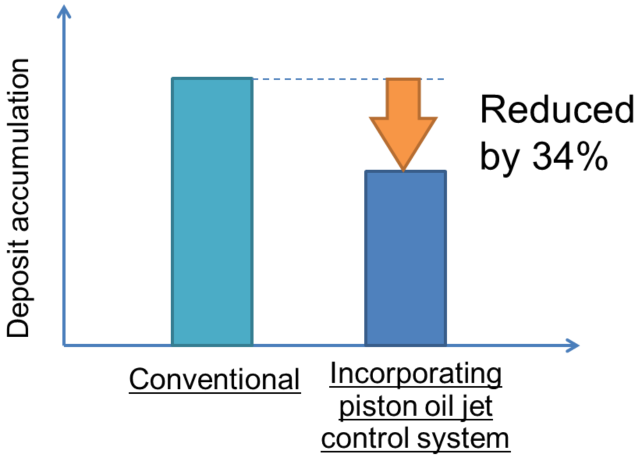

Fig. 22: Piston Top Deposit Accumulation Reduction Effect of Stopping Oil Jets

Figure 23 shows the structure of the dual chamber oil pan and Fig. 24 shows its operating principle. The dual chamber structure creates a separate outer oil chamber. By not circulating the oil in this chamber, the amount of oil circulation is reduced, accelerating oil warm-up. In addition, using the non-circulated oil in the outer chamber as an insulating layer improves the heat insulating properties of the inner chamber from the ambient temperature and increases the speed at which the circulating oil warms up. The structure prevents early deterioration of the circulating oil by ensuring that all the oil maintains equal properties with communication ports, created by adjusting the height of the walls of the inner and outer chambers. The oil in the two chambers mixes through these ports when the engine is stopped. In addition, optimizing the shape of the inner chamber improves the rate of return of oil to the oil strainer intake, thereby minimizing the volume of circulating oil. The baffle plate at the top of the oil pan also reduces agitation of the oil by the crank system. This helps to reduce the volume of circulating oil and also helps to enhance power performance.

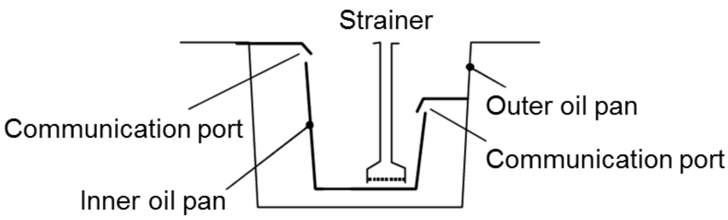

Fig. 23: Structure of Dual Chamber Oil Pan

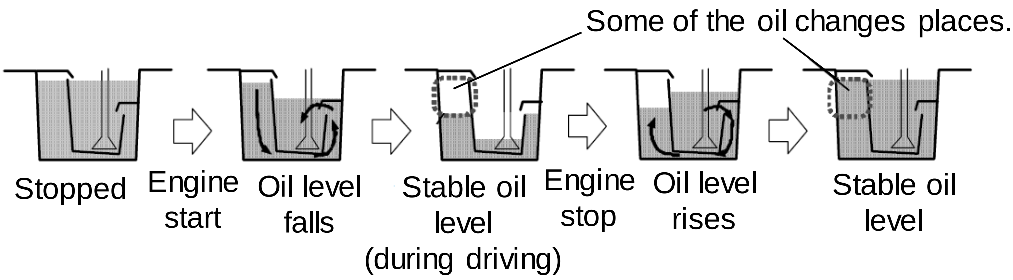

Fig. 24: Operating Principle of Dual Chamber Oil Pan

7 Friction Reduction Measures

This engine contains a large number of design features to help reduce friction by lowering sliding resistance and weight. An offset crankshaft was adopted that lays out the center of the shaft in an offset position with respect to the cylinder bore center. Thermal efficiency was improved by decreasing the piston thrust load to reduce friction loss, and by setting different piston speeds for the compression and expansion strokes. Around both the intake and exhaust valves, the use of thinner roller arms, smaller retainers, beehive-shaped valve springs, and sodium-filled hollow exhaust valves reduce the inertial mass and the valve spring load. Other friction-reduction measures include the adoption of a low sliding resistance timing chain and low friction material chain guide, the application of fine surface reforming (FSR) to the piston skirts and a low-friction coating to the oil sealing lip of the crankshaft, optimization of the lubricant supply to each part, reduction of the oil pump flow volume by adopting a variable oil pump discharge mechanism, and a high-efficiency pump tooth profile. In addition to a newly developed high-strength connecting rod material, which reduces the weight of each rod by 70 g, lowering the reciprocating inertial mass allows the adoption of a lighter crankshaft. The weight reduction measures for the connecting rods and crankshaft lower the weight of the engine by 470 g and help to decrease friction.

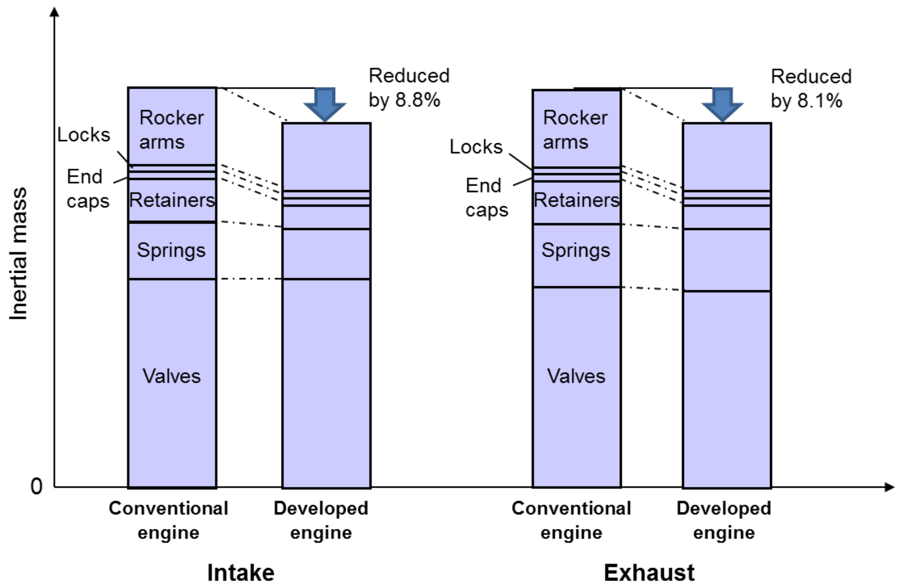

Fig. 25: Effect of Lightweight Valve System

8 Exhaust System

Another key point for a turbocharged engine is to design the exhaust system to ensure a smooth exhaust flow. At the same time, the exhaust system must have a compact shape capable of ensuring the warm-up performance of the catalyst to lower emissions. The relationship between the energy input into the catalyst and the permitted cumulative hydrocarbon emissions under cold conditions was calculated from past engine development experience [1]. To ensure that this engine system complies with the targeted emissions standards, the target specific surface area of the exhaust system was set to 1,100 cm^2/L, based on the relationship with catalyst warm-up performance. In addition, the exhaust temperature is controlled within the appropriate range by the cooling effect within the cylinder head using the integrated exhaust manifold (described above). Then, by setting the relationship between the exhaust temperature and specific surface area of the exhaust system within the appropriate range, emissions were reduced, the heat resistance of the turbocharger was improved, and the λ=1 operating region was enlarged.

For a turbocharged engine, the rate of boost pressure build-up at low engine speeds is extremely important from the standpoint of vehicle acceleration performance. A well-known conventional means of accomplishing this is to enlarge the overlap timing in which both the intake and exhaust valves are open at the beginning of the intake stroke. Then, by guiding the intake air directly to the exhaust system through the combustion chamber, it is possible to create a scavenging effect that improves the boost pressure build-up response. However, in this scavenging process, fresh air that simply passes through the cylinder and does not contribute to combustion flows into the exhaust system. Therefore, if in-cylinder combustion is performed at λ=1, the air-fuel (A/F) ratio at the catalyst becomes lean, which facilitates the emission of nitrogen oxides (NOx). The developed engine addresses this issue by controlling the overall A/F ratio of the gas flow to the catalyst to λ=1. This control maintains good emissions performance during scavenging. Although A/F feedback control using an exhaust A/F sensor is also carried out during scavenging, the rich in-cylinder combustion mixture generates large volumes of hydrogen. This causes deviation of the sensor output value and a drop in the NOx conversion rate. Therefore, the output value of the A/F sensor is corrected to the lean side in accordance with the ratio of the scavenging air flow estimated by an intake system model, thereby improving the catalyst conversion performance. Since the dispersion of individual engines changes the size of this correction value, the feedback control value is set slightly on the rich side to prevent sensitive changes in NOx emissions due to deviations in the A/F ratio. Another issue of controlling the A/F ratio to λ=1 during scavenging is a higher catalyst temperature due to an increase in the amount of conversion reactions by the catalyst. However, a control was added that estimates the catalyst temperature based on the scavenging air flow and stops the scavenging process if a threshold value is exceeded.

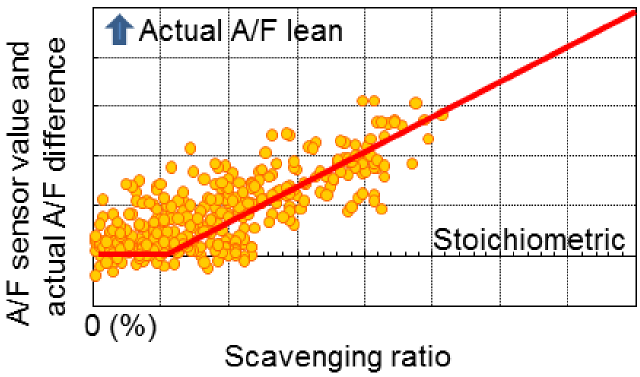

Fig. 26: Scavenging Ratio and A/F Difference

9 LSPI Frequency Reduction Measures

LSPI, which occurs in low-engine speed high-torque regions, is a well-known issue for downsized turbocharged engines. Although the generation mechanism of LSPI is not completely understood, a major contributing factor is the mixture of fuel and oil that accumulates at piston ring crevices due to fuel wetting on the cylinder walls [2]. Reports have been published that attribute LSPI to the self-ignition of drops of this mixture that have scattered throughout the combustion chamber [2], or to the mixture forming deposits, which then generate flakes that scatter throughout the combustion chamber and act as the ignition source (Fig. 27) [3]. Recent research has shown empirically that sequences of LSPIs are triggered by deposits that peel off the cylinder walls [3][4][5]. The following countermeasures to suppress the generation of LSPI were adopted based on these reported mechanisms.

First, to help prevent the direct injection fan spray from wetting the cylinder wall, an improved fan-shaped spray was developed that reduces the penetration of both ends of the spray and adopts a more rounded edge (when viewed from the top) instead of the conventional triangular edge (Fig. 28). Then, the angle of the spray (when viewed from the side) was optimized while avoiding interference with the valves and piston top. In addition, injection timings that are more susceptible to LSPI were identified (Fig. 29) and the injection control was modified to avoid these timings. Research also identified a correlation between the cylinder liner wall temperature and the LSPI frequency due to the evaporation characteristics of the fuel. The occurrence frequency of LSPI was drastically reduced by increasing the cylinder liner wall temperature using the system that promotes the warming up of the cylinder liner walls (described above) and improving excessive cooling, particularly close to the coolant inlet of the cylinder block, using water jacket spacers. Furthermore, LSPI was also reduced by improving oil consumption and adopting a control that reduces internal EGR and the ignition sources present in the EGR by taking advantage of the scavenging effect (Fig. 30).

To ensure reliability when LSPI occurs, the piston second land was designed with sufficient height and stiffness. A Ni-resist (austenitic ductile cast iron) ring carrier was also inserted to secure strength. The h1 thickness of the piston top ring was set to 1.5 mm to ensure sufficient stiffness and the piston top ring was given enough tension to minimize combustion gas blow-by when LSPI occurs.

The engine is also provided with a control to prevent sequences of LSPI by setting a rich A/F ratio in cylinders where LSPI has occurred. This rich control is performed only for the minimum number of cycles necessary to purge the deposit flakes that have peeled from the walls, and is set so that emissions and fuel economy are not affected. If the LSPI sequence does not stop even after the rich control, fuel is cut to the affected cylinder to completely stop the LSPI.

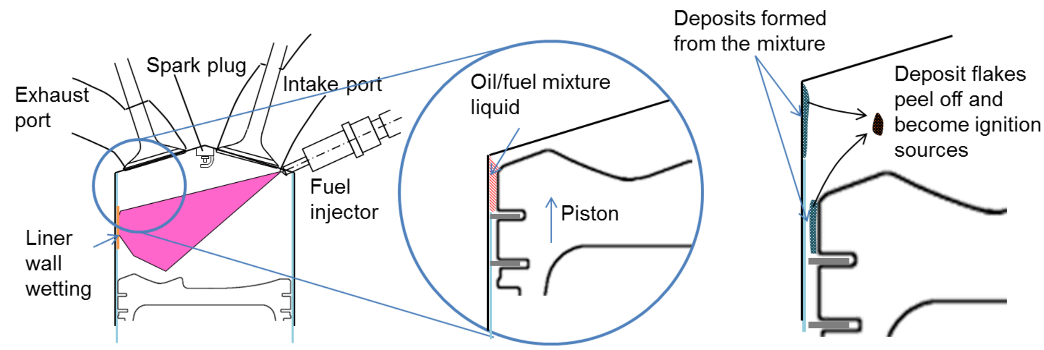

Fig. 27: Accumulation of Deposits as Ignition Sources [3]

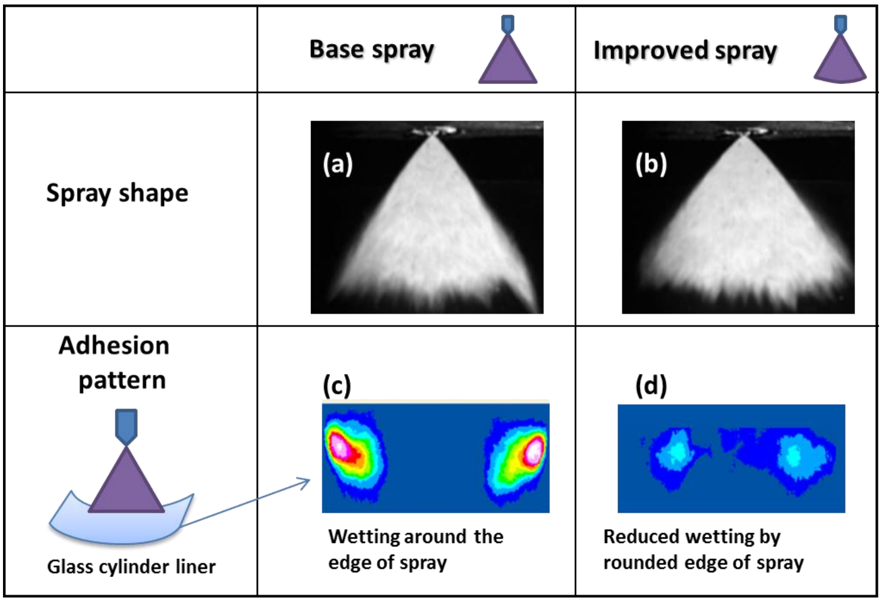

Fig. 28: Reducing Liner Wall Wetting by Spray Shape

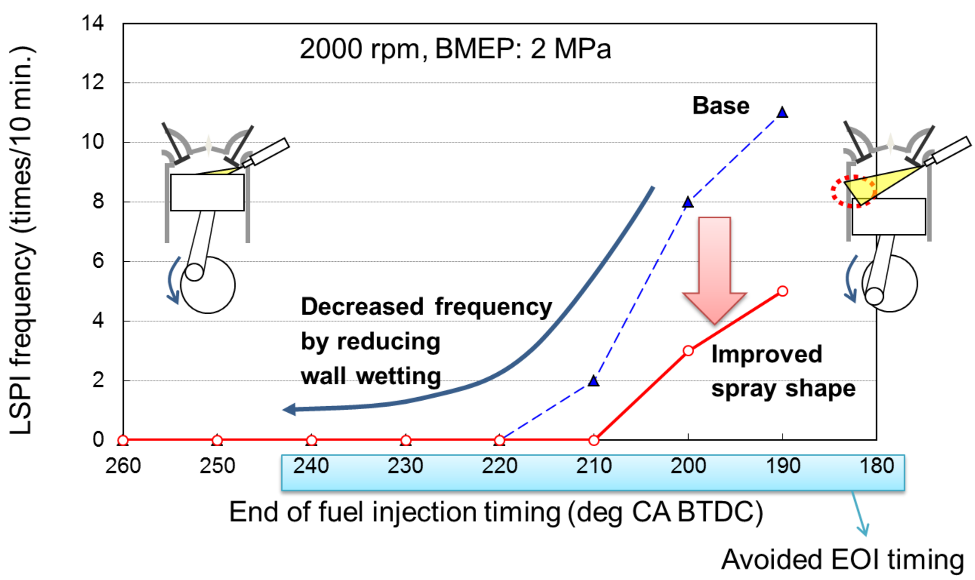

Fig. 29: Reducing LSPI Frequency by Spray Shape and Injection Timing

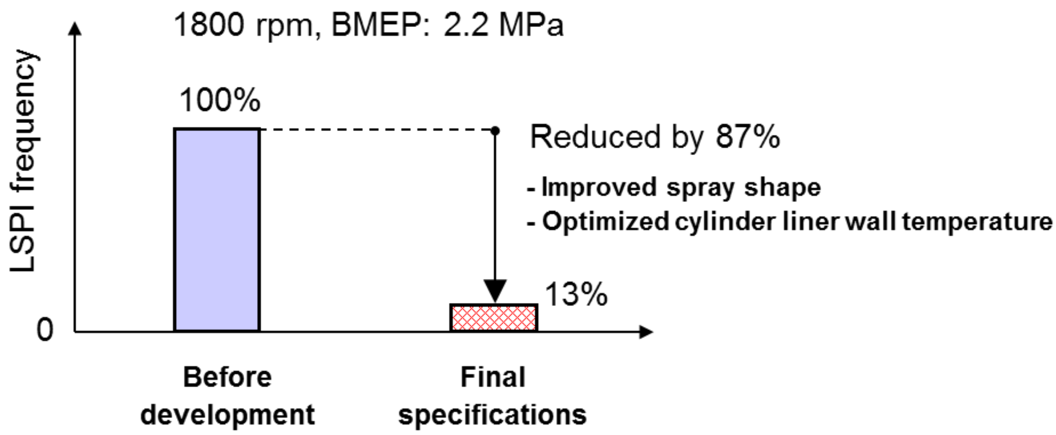

Fig. 30: Reduction in LSPI Frequency

10 Development of Dedicated Engine Oil for Turbocharged Engines

As described above, it has been hypothesized that one of the mechanisms of LSPI is the mixture of fuel with the oil on the inner cylinder walls. Drops or deposit flakes from this mixture then scatter throughout the combustion chamber and form ignition sources. This requires oxidation reactions to take place until ignition occurs. However, engine oil contains various components that promote such reactions. Reports have shown that calcium (Ca), which is present as a metallic detergent, greatly increases the LSPI frequency [6][7]. In contrast zinc dialkyldithiophosphate (ZnDTP) and molybdenum dialkyldithiocarbamate (MoDTC) are known to reduce the LSPI frequency. These components suppress oxidation reactions caused by peroxides, a fact which suggests that the susceptibility of drops or deposits to oxidation reactions has a major effect on the LSPI frequency.

Based on these findings, an engine oil was developed that can reduce the LSPI frequency while maintaining the required performance of an engine oil. To ensure sufficient durability as a lubricant with reduced Ca, the development targeted equivalent performance to a C2 oil as defined by the representative low-ash oil standards published by the European Automobile Manufacturers' Association (ACEA). In addition to optimizing the dispersant and detergent, a synthetic poly-alpha-olefin (PAO) oil was blended into a high-performance group 3 base oil. The targeted performance aspects were achieved with a low-viscosity grade of 0W-20.

Figure 31 compares the test results for LSPI frequency with the developed oil and a commercially available GF-4 standard 0W-20 oil as defined by the International Lubricant Standardization and Approval Committee (ILSAC), which was commonly used in the Japanese and U.S. markets until 2011. The LSPI frequency with the developed oil is less than one-tenth the frequency with the mainstream ILSAC-standard oil, which represents a substantial reduction.

The tests carried out to verify the LSPI frequency shown in Figs. 30 and 31 used a test engine specially designed to be susceptible to LSPI. The engine was operated continuously for one hour at the minimum engine speed required to generate maximum torque under lowered coolant temperature conditions. These conditions differ from the real-world driving conditions of an actual vehicle and were designed to be particularly favorable for LSPI generation.

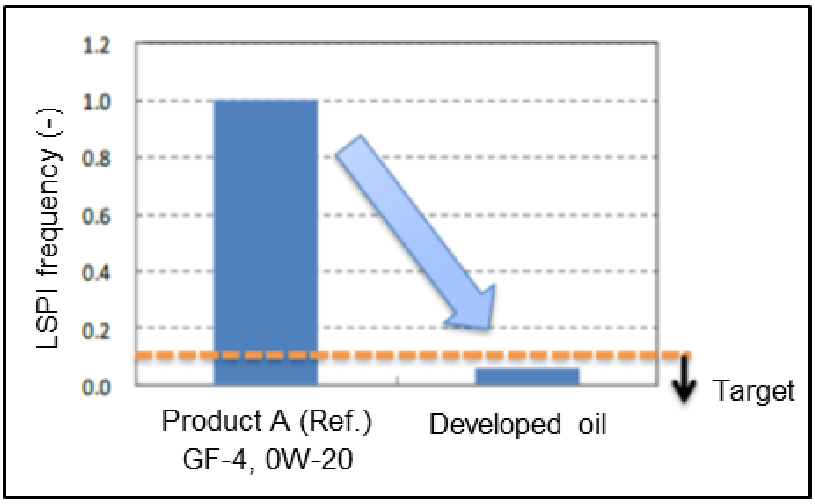

Fig. 31: LSPI Test Results of Developed Engine Oil

11 Oil Deterioration Reduction Measures

Toyota's gasoline NA engines are developed with a particular focus on crankcase ventilation. Equivalent crankcase ventilation to a NA engine was achieved in this turbocharged engine. In addition to the conventional use of manifold negative pressure to ventilate the crankcase, this engine adopts a forced ventilation system using an ejector under boosted conditions to ventilate the crankcase in all engine operating regions. This ensures the same oil maintenance interval as an NA engine even with the same mineral-based engine oils commonly used in NA engines.

Figure 32 shows the positive crankcase ventilation (PCV) system for this turbocharged engine. The operating principle of the ejector is as follows. Some of the supercharged air is injected from the nozzle as a high-pressure driver gas, forming a high-speed low-pressure jet and causing blow-by gas to be sucked in from the suction port (Fig. 33). As shown by the relationship between the intake manifold pressure and ventilation flow (Fig. 34), the crankcase can be ventilated over a wide range of intake air conditions from negative pressure to boosted conditions. In addition, since a turbocharged engine generates large amounts of blow-by gas, a two-chamber structure was adopted with No. 1 and 2 separator chambers to separate the oil (Fig. 35). This structure improves the separation performance of the oil within the blow-by gas.

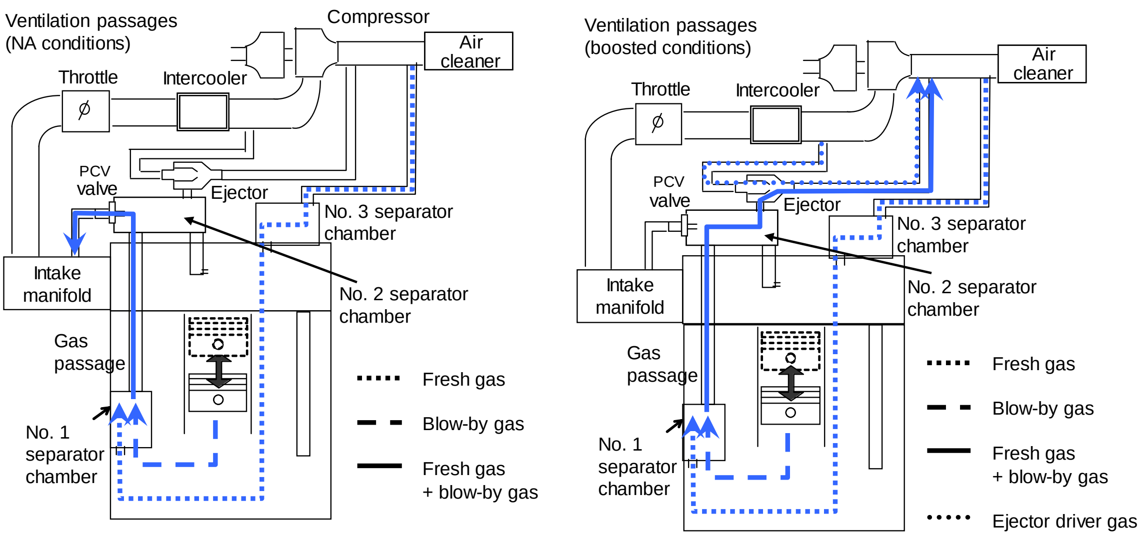

Fig. 32: Turbocharged Engine Crankcase Ventilation System

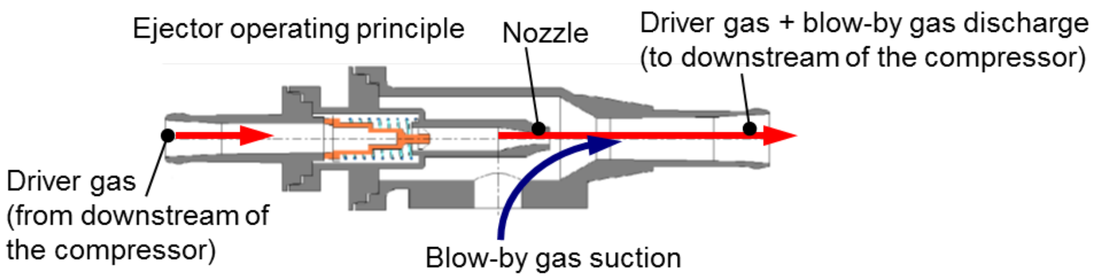

Fig. 33: Ejector Structure and Operating Principle

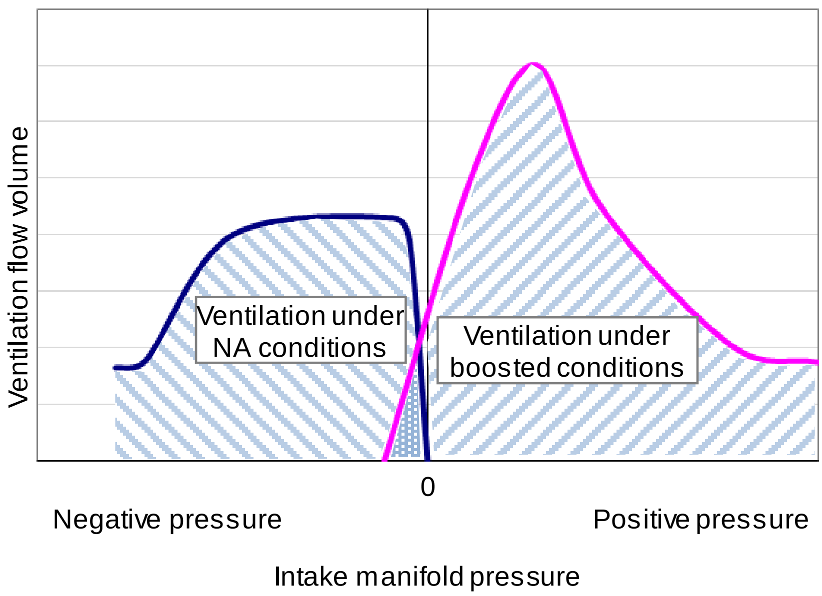

Fig. 34: PCV System Ventilation Flow Volume

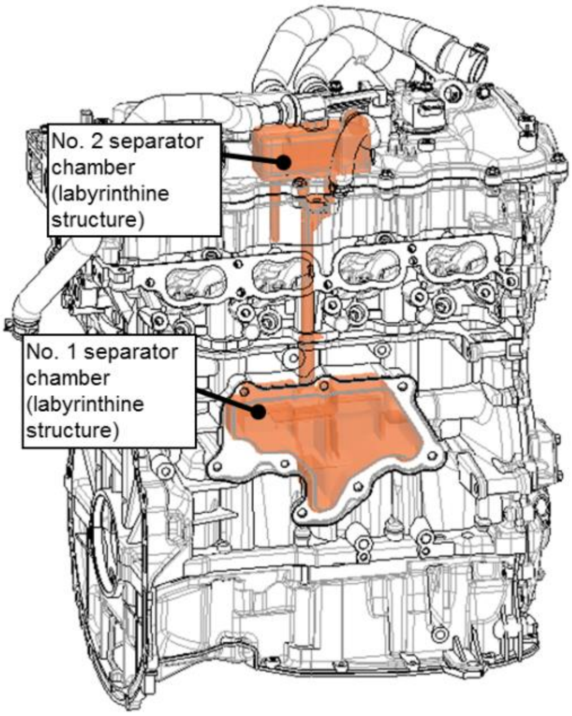

Fig. 35: Oil Separator Structure

12 Productivity

On April 1, 2013, Toyota established the Unit Center as a new organization to develop highly competitive engine, transmission, and hybrid system components, and bring them promptly to market. In addition, Toyota decided to bring together its separately located R&D and production engineering (PE) functions to consolidate the development of powertrain components under one roof in the new Powertrain Development and Production Engineering Building. However, before the establishment of this new organization, Toyota created a project team of engineers from the design, PE, and manufacturing fields in January 2011 to start developing this engine through joint design and simultaneous engineering. By including PE and manufacturing engineers from the initial development phase, new technologies and manufacturing methods were developed while identifying the key production requirements (such as machining datums, bore pitch, and basic crankshaft specifications). As a result, this engine can be produced using the same production facilities as the current mass-produced NA AR engine series. Toyota's engine assembly lines are configured around a design principle consisting of 8 sub-assemblies (Fig. 36). The design of the new turbocharged engine also adopts this 8 sub-assembly structure, which forms the basis of its assembly lines. This development process allowed the productivity of the engine to be verified using mass-production facilities at an early stage, helping to enhance manufacturing quality.

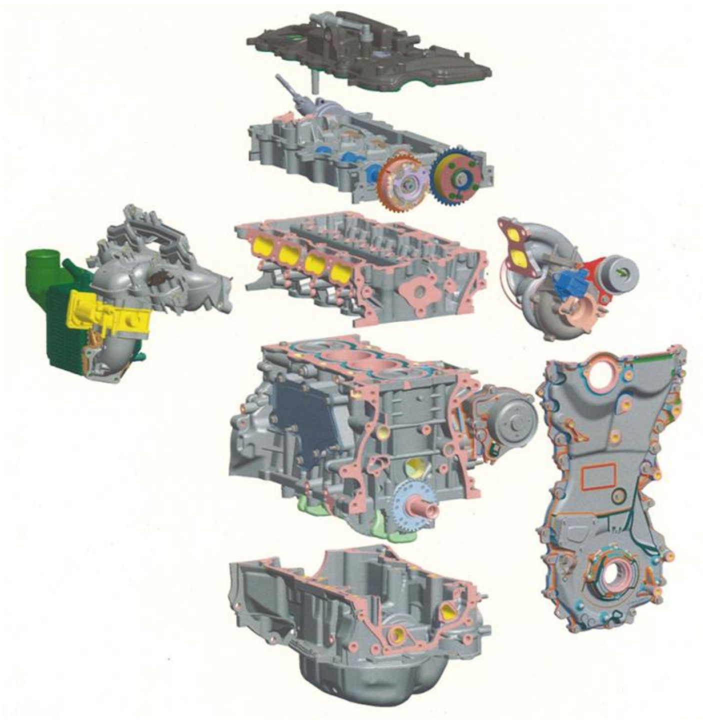

Fig. 36: 8 Sub-Assembly Structural Blocks

13 Engine Performance

The adoption of turbocharged direct injection combustion, friction reduction technologies, and the Atkinson cycle (described above) creates a torque curve with a high and wide torque band from low to high engine speeds (Fig. 37). The maximum thermal efficiency of the engine is 36%, one the highest for a turbocharged engine. The fuel economy region below 250 g/kWh is 1.5 times larger than Toyota's 3.5-liter NA engine (Fig. 38) and the λ=1 operating region has been expanded up to a vehicle speed of 190 km/h.

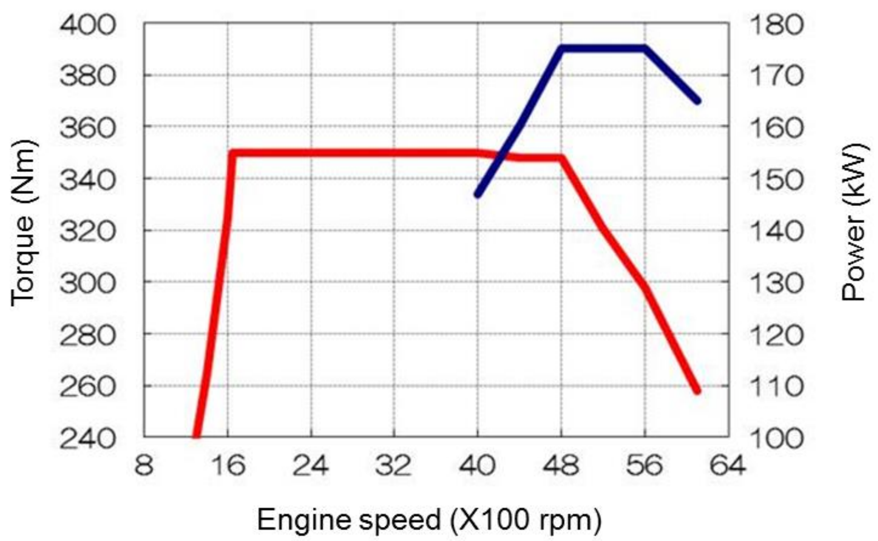

Fig. 37: Torque Curve

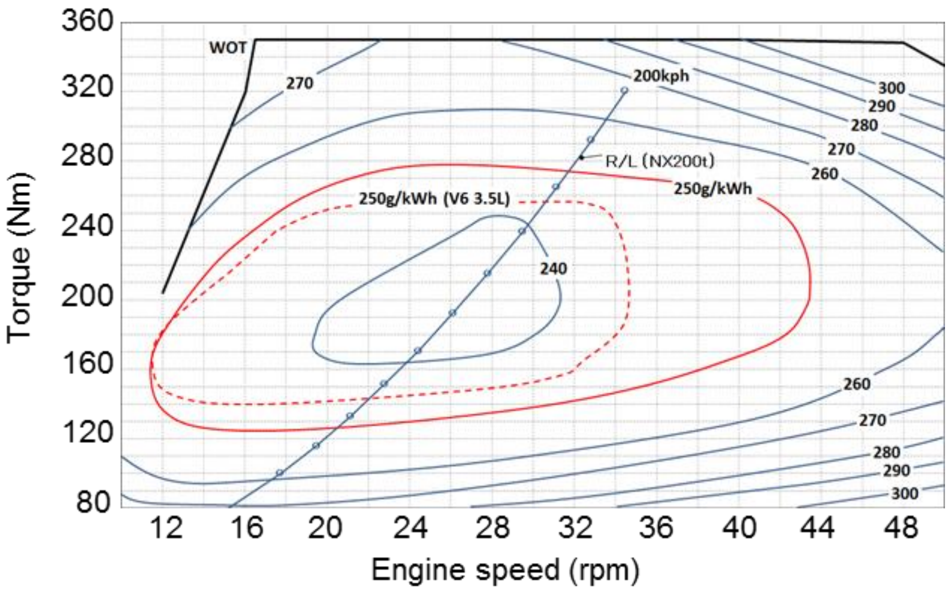

Fig. 38: Brake Specific Fuel Consumption (BSFC) Map

The engine enables enhanced vehicle acceleration response. Measures such as reducing the size and increasing the efficiency of the turbocharger, and adopting scavenging control improved the rate of boost pressure build-up by 50% compared to prototypes. Cooperative control with the transmission helps to achieve smooth acceleration (Fig. 39).

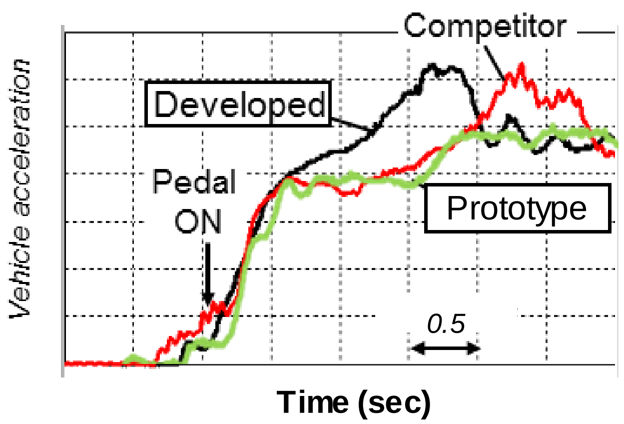

Fig. 39: Vehicle Acceleration

14 Conclusion

This paper has described a range of the new technologies incorporated into the Toyota 2.0-liter inline 4-cylinder ESTEC D-4ST engine. By taking advantage of these technologies, the engine achieves quick response and a high and wide torque band from low to high engine speeds, as well as larger operating regions in which excellent fuel economy and λ=1 combustion can be achieved. The resulting high levels of both fun-to-drive and environmental performance are the ideal expression of Toyota's next-generation engine development.

In addition to basic structural elements such as the cylinder head, highly functional and critical components for engine performance, such as a twin-scroll turbocharger, VVT-iW, and a direct injection high-pressure fuel pump, were developed and fabricated in-house by Toyota. In this way, Toyota ensures high-quality for both the design and manufacture of this engine.

The developed engine is compliant with emissions standards around the world, such as LEV III (ULEV 125) in North America, Euro 6, China 5, and J-SULEV. It is planend to adopt this engine in various models to meet the needs of customers all over the world.

15 Acknowledgments

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