

Development of Gasoline Turbo Engine Conforming to U.S. ULEV2 Regulations

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ABSTRACT

Honda has developed a 2.3L 4-cylinder gasoline turbo engine that balances high power output with high fuel economy and low emissions. The new engine adds a newly developed variable-capacity turbocharger to Honda's proprietary i-VTEC engine technology. This addition resulted in a peak power output of 179 kW with the low-speed torque characteristics of a 3.5L normal aspirated engine due in part to a high boost-pressure response. Rapid activation of the exhaust catalyst is achieved by positioning it directly underneath the turbocharger and by reducing the heat capacity of the exhaust system via an exhaust manifold constructed out of aluminum alloy. This, coupled with a highly optimized catalyst metal loading has enabled this powertrain to meet the requirements of U.S. ULEV 2 regulations. This engine will be used in a new model SUV for the U.S. market. The vehicle will display a dynamic performance equal to or better than that of SUVs fitted with 3.0-3.5L normal aspirated engines, while at the same time achieving top-in-class fuel economy.

1. Introduction

At the same time that environmental issues are being addressed on a global scale, the price of gasoline has risen markedly. Given these circumstances, the need for enhanced automotive fuel economy has grown, from the perspective of not only reducing tailpipe emissions, but also of CO₂ reduction. Several different approaches exist when considering automotive fuel economy enhancement technologies, but one approach is to reduce engine displacement without sacrificing power by means of forced induction. Forced induction via the use of a turbocharger leads to lower friction loss than with mechanical supercharging, and is appropriate for enhancing fuel economy through this method of reduced displacement. However, response and torque at low engine speeds, when there is little exhaust energy, are not as good as in a

large displacement, normal aspirated engine, and it was thought that applying supercharging to heavy vehicles would lead to reduced drivability. To address this, Honda's new engine, uses a Variable Flow Turbocharger (VFT), which enhances low-speed torque and response. Combining this VFT with an automatic transmission optimized for use with a turbo engine provides performance and drivability similar to that of other vehicles with large engine displacements. A turbocharger, however increases the heat capacity of the exhaust system, which inhibits exhaust catalyst warm-up, and thus greatly affects exhaust emission reduction performance at start-up. This engine conforms to U.S. ULEV2 standards through the use of Honda's original i-VTEC mechanism, reducing the heat capacity of the exhaust system, and optimizing exhaust catalyst performance. This paper describes an outline of the newly developed gasoline turbo engine, along with its major technologies.

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Table 1 Engine specifications

Engine code		K23A	K24A
Cylinder configuration		In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)		86 × 99	87 × 99
Displacement (cm ³)		2300	2354
Compression ratio		8.8 : 1	9.7 : 1
Valve train		DOHC i-VTEC	DOHC i-VTEC
Number of valves		4 per cylinder	4 per cylinder
Valve diameter (mm)	Inlet	35	35
	Exhaust	30	30
Turbo charger		Variable flow turbocharger	–
Impeller external diameter (mm)	Compressor	56	–
	Turbine	32	–
Exhaust manifold		Water-cooled aluminum alloy	Stainless steel pipe
Catalyst [vol.(L)]		Close coupled [1.4] + underfloor [1.0]	Underfloor [1.7]
Recommended gas (octane rating)		Unleaded premium (RON95)	Unleaded regular (RON91)
Max. power (kW/rpm)		179 / 6000	125 / 5800
Max. torque (Nm/rpm)		353 / 4500	220 / 4000

2. Development Goals

The following targets were set to develop an engine for use in a compact SUV for the U.S. market.

- (1) Achieve best-in-class fuel economy with acceleration performance equivalent to SUVs equipped with normal aspirated 3.0–3.5 L engines.
- (2) Achieve a smooth and responsive starting acceleration performance with no feeling of stagnation.
- (3) Achieve the best peak power among vehicles with turbo engines that conform to U.S. ULEV2 standards, and peak torque on par with normal aspirated 3.5 L engines.

3. Overview of the Engine and Major Specifications

3.1. Overview of Engine

Table 1 compares the major specifications of this engine with those of the base 2.4 L normal aspirated ACCORD (K24A) engine, and Fig. 1 shows the external view of the newly developed engine.

Based on the framework of the K24A 4-cylinder i-VTEC engine⁽²⁾ used in the ACCORD, various measures were taken, including strengthening the reciprocity system that accompanies the use of a turbocharger. Engine displacement was changed to 2.3 L by reducing the K24A cylinder bore by 1 mm to 86 mm. The valve-train system is the i-VTEC used in the K24A. The i-VTEC mechanism used in this engine combines a VTEC (variable valve timing & lift) mechanism with VTC (camshaft phase continuation variable control) on the intake side camshaft. A VTEC mechanism is used for the intake valves, switching between a combustion-stabilizing 1-valve pause and a high charge-efficiency 2-valve drive, according to the driving range. The combination of 1-valve pause and high swirl-intake ports is effective in stabilizing combustion during ignition timing delay immediately after start-up. This allows for ignition retard immediately after starting, which in turn leads to rapid catalyst warm-up. The VTC incorporated in the intake camshaft contributes to a reduction in feed gas NO_x through the

introduction of an internal EGR, while also contributing to enhanced fuel economy by reducing pumping losses. Moreover, a water-cooled aluminum alloy exhaust manifold, developed for this engine, minimizes any increase in the heat capacity of the exhaust system due to the installation of the turbocharger, and achieves rapid activation of the catalyst during start-up. The conventional cylinder head with integrated exhaust manifold⁽⁴⁾ that is used in many Honda engines has an integrated structure. In this set-up, all of the exhaust ports, from each cylinder to the collector, are completely housed inside the cylinder head. With the turbo engine, the exhaust manifold portion is separate, which enlarges the water jacket surface area. This enhances water cooling performance around the exhaust ports, which exhibit high exhaust pressure and high temperatures due to the installation of the turbocharger. It also enhances the cooling performance of the surfaces between the turbocharger and exhaust manifold. Figure 2 shows the structure of the exhaust manifold water jacket.

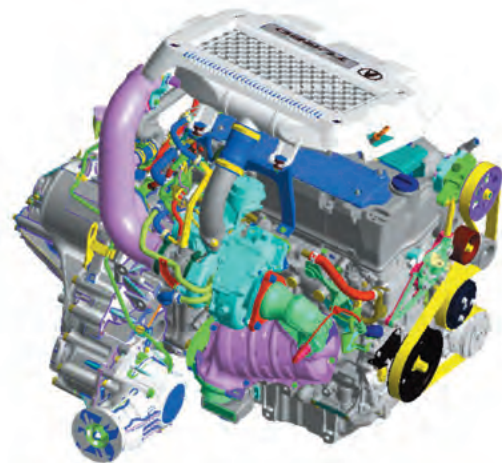


Fig. 1 K23A DOHC i-VTEC turbo engine

3.2. Overview of the Turbocharger

Figure 3 is an overview of the VFT used by this engine. The VFT is a redesigned variable capacity turbocharger⁽¹⁾. The turbine has two scrolls – inner and outer circumferences – separated by the fixed vane. A flow control valve, located at the turbine inlet port, directs exhaust gas to the inner or outer scrolls. This allows the turbine capacity to be changed arbitrarily, providing both the characteristics of a small-capacity turbine, emphasizing low-speed torque, and of a large-capacity turbine, emphasizing high power. The variable capacity turbines used in diesel engines are generally Variable Nozzle Turbochargers (VNT), but these turbochargers have a complex mechanism in the variable nozzle part, and have many issues concerning heat resistance. It is difficult to adopt this technology to high-power gasoline engines because of their high temperature exhaust gases. Compared to VNT, the VFT has fewer moving parts. The sliding part of the flow control valve, which is the VFT's only moving part, is located where it is not in direct contact with high-temperature exhaust gases, so the VFT can be used in high-power gasoline engines. The flow control valve and waste gate are driven by boost pressure, via their own separate positive pressure actuators. In addition, the actuators' applied pressure is electronically controlled by solenoid valves.

4. Supercharger System and Power Performance

4.1. Benefits of VFT Use

Turbo engines can recover energy in exhaust gasses, making them more efficient than engines with mechanical superchargers. However, some of the issues affecting turbo engines include insufficient torque at low engine speeds, when there is little exhaust energy, and significant delayed response times when shifting from low-load to high-load ranges. The newly developed engine addresses these issues by using the VFT. Figure 4 compares the W.O.T. torque characteristics of conventional turbochargers to those of the VFT. The VFT provides a wider range of torque characteristics, including both the low-speed range characteristics

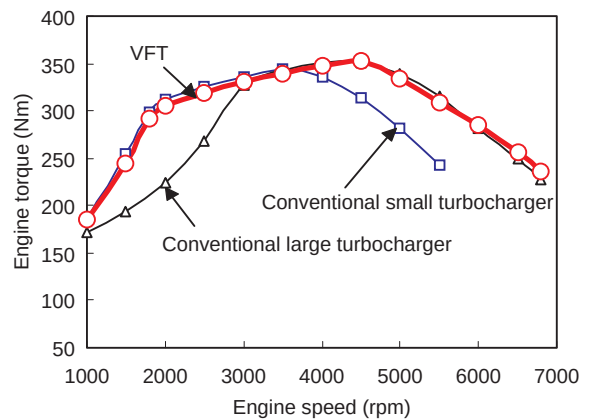


Fig. 4 Effect of VFT on engine torque

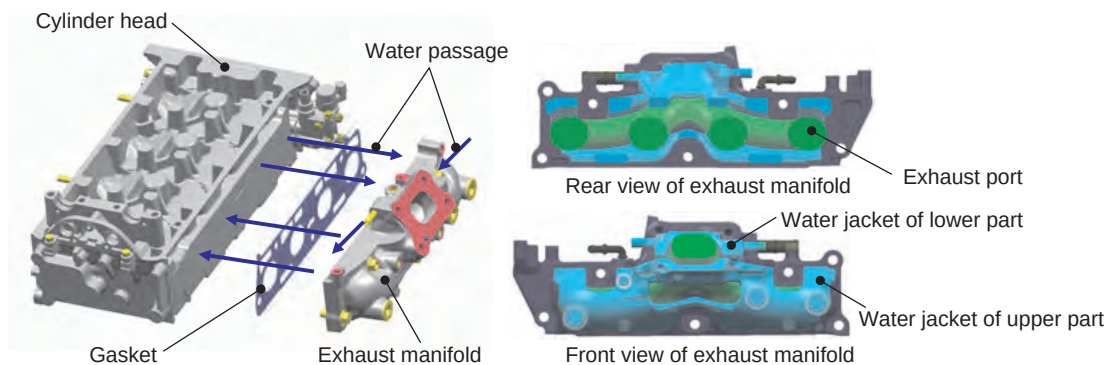


Fig. 2 View of water-cooled aluminum alloy exhaust manifold

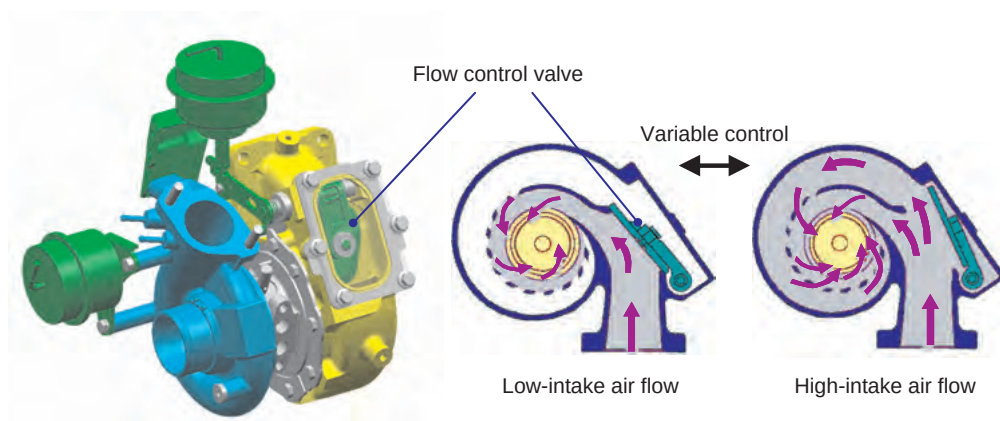


Fig. 3 View of VFT

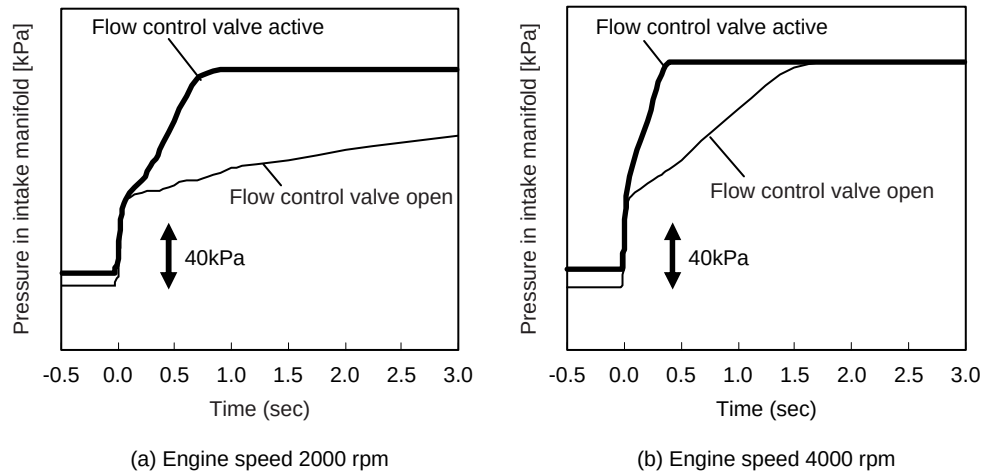


Fig. 5 Effect of flow control valve on boost pressure response

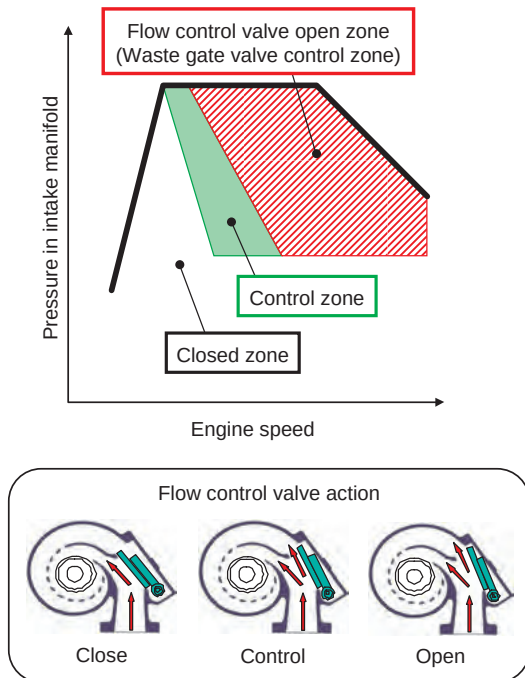


Fig. 6 VFT control zone

of a small turbocharger and the high-speed range characteristics of a large turbocharger.

As an evaluation of boost pressure responsiveness, Fig. 5 shows boost pressure characteristics when the throttle changes from closed to wide open at fixed engine speeds.

With the VFT flow control valve wide open (no flow control), turbo characteristics are equivalent to those of a conventional large turbocharger. At 2000 rpm (low speed), the target boost pressure cannot be achieved without implementing flow control. However, when flow control is applied, it is possible to achieve the target boost pressure within 1.0 sec. [Fig. 5(a)]. At 4000 rpm, the time it takes to reach the target boost pressure drops from 1.7 sec. to 0.4 sec. with flow control applied. This is less than 1/4th the time required when the flow control valve is not used [Fig. 5(b)].

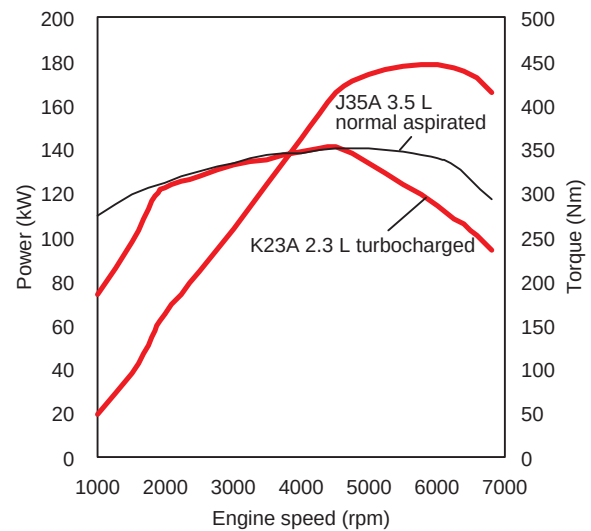


Fig. 7 Engine performance

4.2. Boost Pressure Control

Boost pressure is controlled, according to driving conditions, by the flow control valve and the waste gate valve. These valves are driven by two independent actuators. The flow control valve opening is basically set according to intake airflow. The boost pressure is controlled by the flow control valve in the low intake airflow range, and by the waste gate valve in the high intake airflow range. Figure 6 is a schematic of the boost pressure control ranges.

4.3. Power Performance

While reducing intake and exhaust resistance, this engine incorporates a charge air cooling effect thanks to a large capacity low pressure loss intercooler. All its technologies combined achieves a maximum power of 179 kW and a maximum torque of 353 Nm. Figure 7 shows this engine's W.O.T. power characteristics, and for comparison, the W.O.T. power characteristics of the J35A (3.5 L V6) used in the ACURA RL. In the normal operating range of 2000–4500 rpm, this engine achieves torque on a level equal to that of a normal aspirated 3.5 L engine.

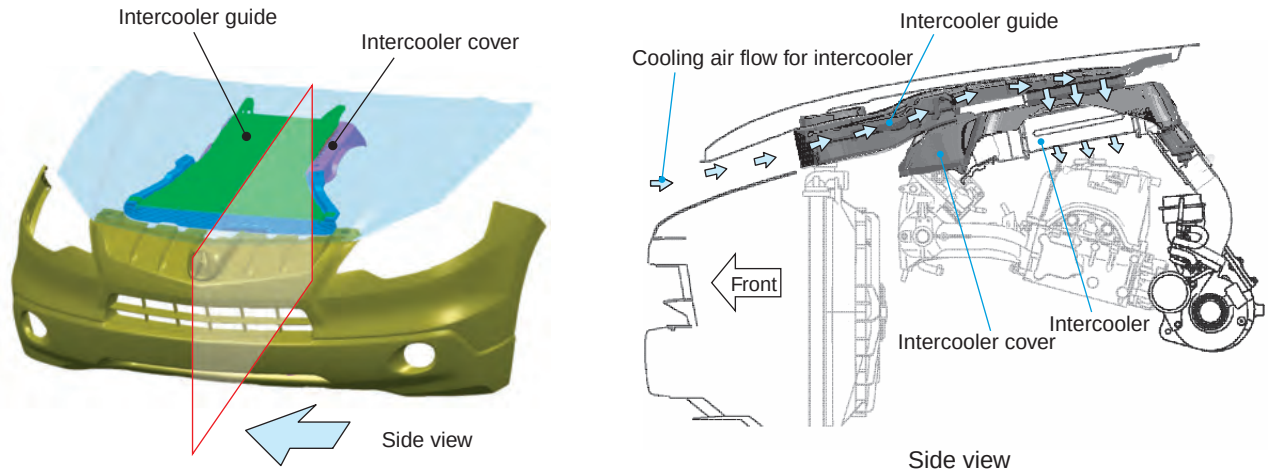


Fig. 8 View of intercooler guide

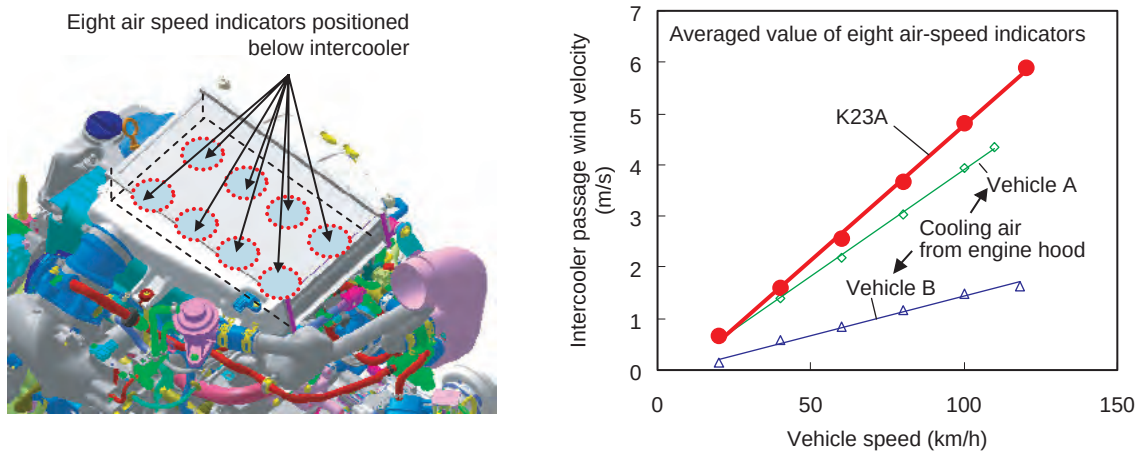


Fig. 9 Intercooler passage wind velocity

The intercooler is positioned at the top of the engine, and cooling air taken in from the front of the vehicle is directed by the intercooler guide and cover, as shown in Fig. 8. An outline of the intercooler guide is also shown in the figure.

Eight air speed indicators positioned directly below the intercooler constantly evaluate intercooler efficiency with respect to vehicle speed. Since cooling air is taken in at the front of the vehicle, an intake airspeed of 4.8 m/s is ensured at a vehicle speed of 100 km/h. This results in better cooling performance compared with conventional set-ups where the cooling air is taken in from the engine hood, as shown in Fig. 9.

5. Engine Unit Fuel Economy

Typically, forced induction engines must have a low compression ratio to avoid knocking, which in turn can cause lower fuel economy than in normal aspirated engines. To minimize the drop in fuel economy and make downsizing through forced induction effective, it is very important to address the issue of knock. In this engine, knocking was avoided by modifying the water jacket shape around the combustion chamber. The use of small diameter long-reach spark plugs also helped prevent a drop in fuel economy. With any forced induction engine, torque is directly proportional to boost pressure. In addition, high boost pressure calls for a lower

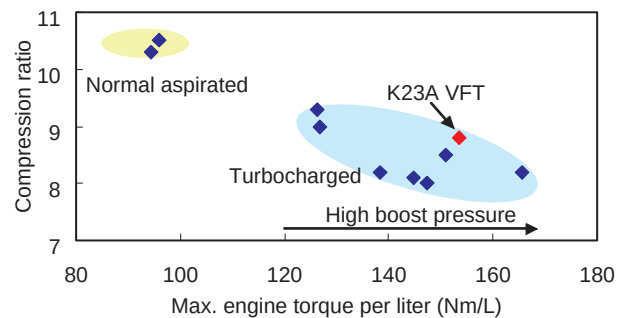


Fig. 10 Positioning of compression ratio

compression ratio to help reduce knocking. However, as shown in Fig. 10, torque per unit of displacement of this engine is enhanced by high boost pressure, while at the same time employing a higher compression ratio than that of many other charged engines.

As shown in Fig. 11, in addition to the higher compression ratio and reduction in pumping loss achieved with the internal EGR using the VTC, BSFC was reduced roughly 12% compared to that of a normal aspirated 3.5 L engine with an equivalent maximum torque.

Additionally, when looking at the relationship of BSFC to normal aspirated engine displacement, as shown in Fig. 12, this engine is positioned as equivalent to a normal aspirated 2.5 L engine.

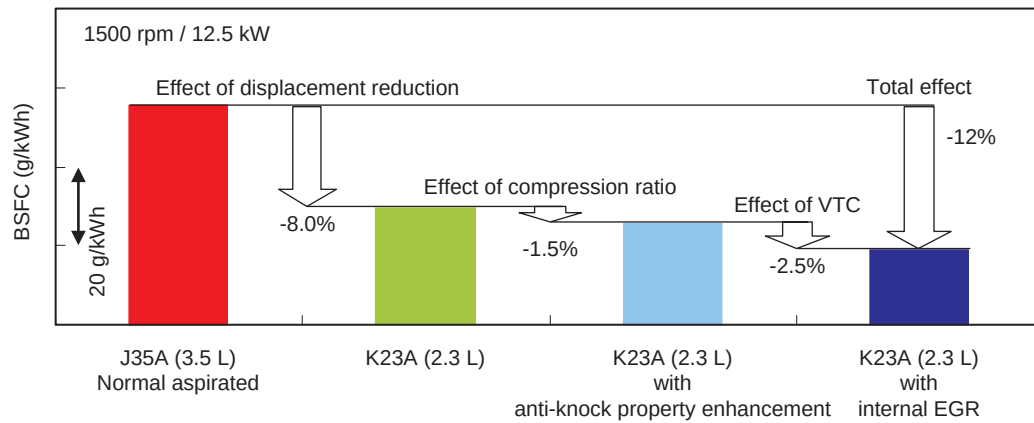


Fig. 11 Effect of displacement reduction on BSFC

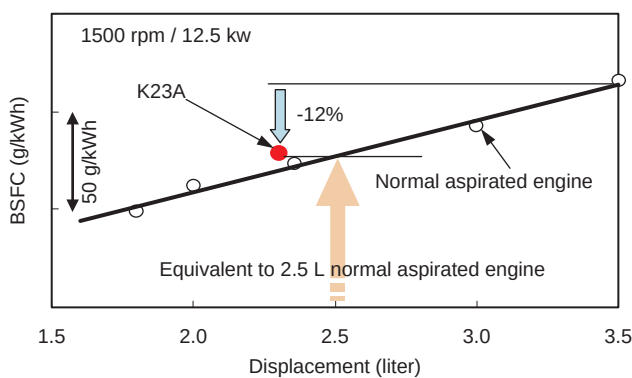


Fig. 12 Positioning of BSFC

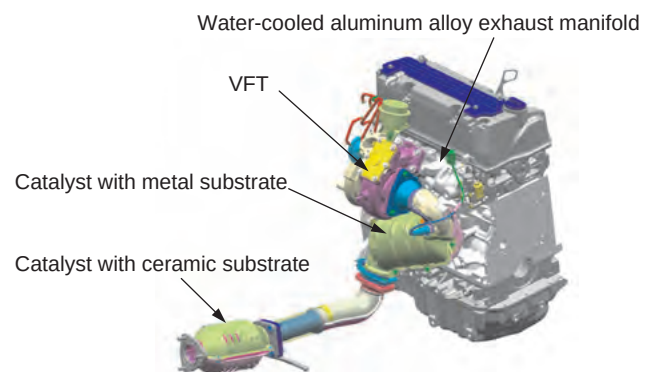


Fig. 13 View of exhaust system

6. Low Emission Technologies

The exhaust emission reduction system incorporates a metal substrate catalyst located directly beneath the VFT, as well as a ceramic substrate under-floor catalyst. Figure 13 shows this engine's exhaust system.

Because a water-cooled aluminum alloy exhaust manifold is used in the engine, the catalyst temperature 20 sec. after start-up was increased by approximately 120 °C over that of a conventional stainless steel exhaust manifold, contributing to rapid activation of the exhaust catalyst. Figure 14 shows the exhaust catalyst temperature change over time immediately after start-up.

A metal substrate with a lower cell density was used for the catalyst positioned immediately beneath the turbocharger to lower the exhaust back-pressure. Despite the fact that the metal substrate has higher thermal transfer characteristics than those of a ceramic substrate, which is a disadvantage in terms of warm-up time, this change was necessary to meet power targets. With this engine, the metal substrate was divided into two parts and the effect of the catalyst segmentation ratio on warm-up characteristics was studied using a 2D simulation of the catalyst reaction. This used chemical reaction and heat transfer models to calculate the catalyst temperature from the data on exhaust gas introduced into the catalyst. Dividing the catalyst enhanced the warm up characteristics

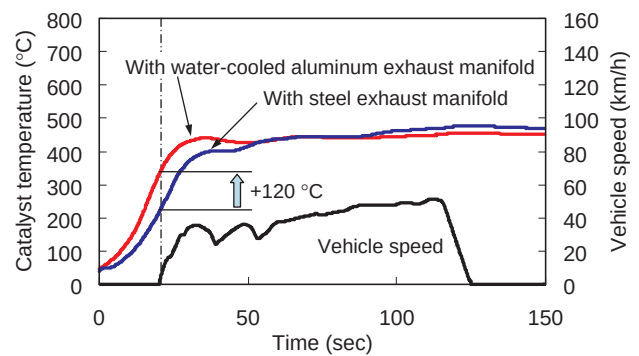


Fig. 14 Effect of water-cooled exhaust manifold on catalytic converter warm-up characteristics

of the upstream catalytic converter due to the insulating effect of the gap created between the bricks. It was shown that reducing the capacity of the upstream catalyst was more effective in enhancing warm-up characteristics. A comparison of warm-up characteristics in relation to the catalyst segmentation ratio is shown in Fig. 15.

From the results of the simulation, setting the catalyst segmentation ratio to 0.45 L upstream and 0.95 L downstream enabled catalyst temperature to rise by an additional 20 °C compared to when the catalyst was divided equally. As a result of

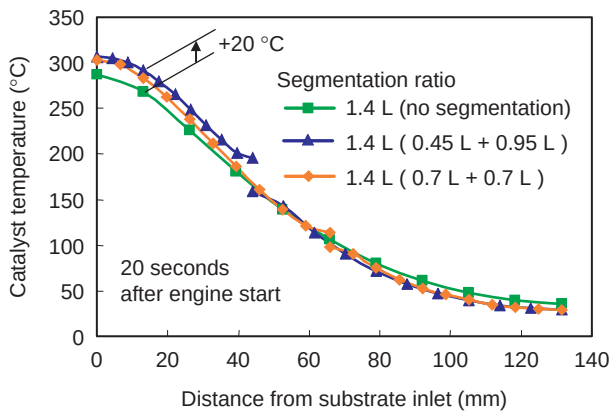


Fig. 15 Simulation results for catalyst temperature

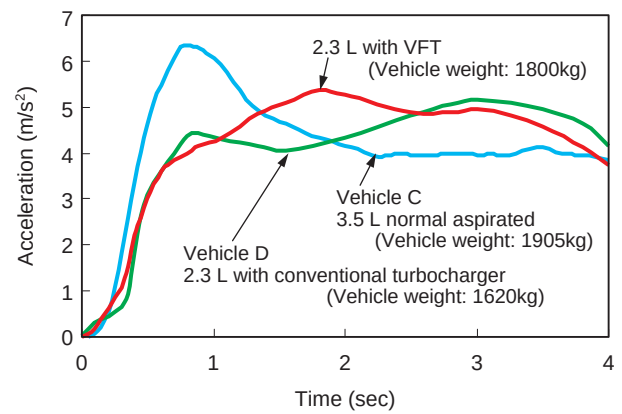


Fig. 17 Comparison of take-off acceleration performance

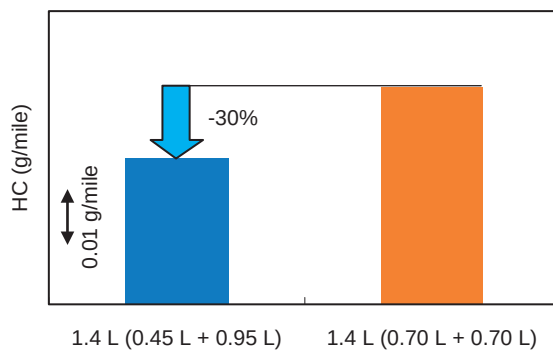


Fig. 16 Tail-pipe emissions

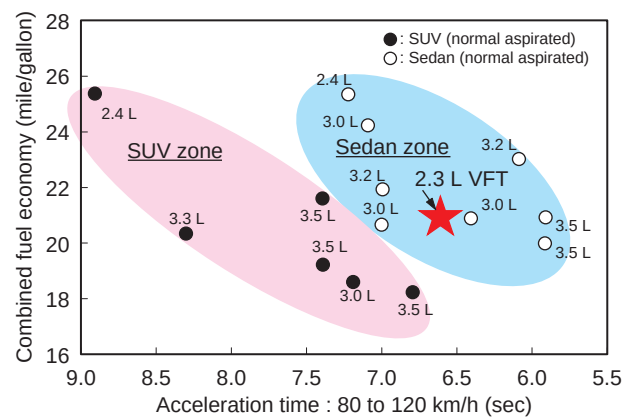


Fig. 18 Positioning of acceleration time and fuel economy

applying this catalyst segmentation ratio to the engine, it was possible to reduce the HC concentration in exhaust gases by 30% in U.S. emissions FTP mode (cold start), as shown in Fig. 16.

In addition to low emissions technologies⁽³⁾, such as the i-VTEC carried over from the K24A, enhancing the catalyst's warm-up characteristics using the aforementioned exhaust system allowed U.S. ULEV2 emission standards to be met.

7. Vehicle Performance and Fuel Economy

7.1. Standing Start Acceleration Performance

Torque converter characteristics of the automatic transmission were optimized with response characteristics of the VFT engine in mind to achieve the targets of smooth yet firm starting acceleration with no feeling of stagnation or lag. Figure 17 compares the starting acceleration performances of an SUV with the VFT engine installed, a vehicle with a normal aspirated 3.5 L engine (Vehicle C), and a vehicle with a 2.3 L engine with a conventional large turbocharger (Vehicle D).

Vehicle C, with the large displacement normal aspirated engine, generates maximum acceleration immediately after the throttle is wide open using the torque converter amplification effect. Then acceleration gently drops off. Vehicle D, using an engine with a conventional large turbocharger, reaches an acceleration peak somewhat later due to the effects of turbo lag, followed by a gentle drop in acceleration. After that, acceleration once again rises as boost pressure rises, resulting in a feeling of acceleration stagnation.

With the newly developed engine, the VFT makes the boost pressure rise earlier, and prevents a drop in acceleration, thus eliminating the feeling of acceleration stagnation produced by a conventional high-powered turbo engine.

7.2. Vehicle Fuel Economy

The fuel economy achieved with the VFT engine was a U.S. label combined 21 mpg. Compared to SUVs in the same class, it was best in both acceleration performance and fuel economy. Figure 18 shows the vehicle's relative acceleration performance and U.S. combined fuel economy.

8. Conclusion

One of the major differences in the new engine is the use of the newly developed VFT. This ensures driving performance that compares favorably to that of a large displacement normal aspirated engine. The fuel economy is also benefited by reducing engine displacement. In addition to good acceleration performance and fuel economy the forced induction VFT engine achieved low emissions by enhancing catalytic converter warm-up characteristics through technologies such as the aluminum alloy exhaust manifold and i-VTEC. The following results were obtained:

- (1) A peak power of 179 kW was achieved with maximum boost pressure being available at engine speeds of 2000 rpm or less. This made forced induction possible at low engine speeds with little response delay providing a smooth and responsive starting acceleration with no feeling of stagnation.
- (2) The development of an aluminum alloy exhaust manifold and optimization of the segmentation ratio of the metal substrate of the catalytic converter located immediately beneath the turbocharger enabled catalyst warm-up characteristics to be enhanced and U.S. ULEV2 emissions regulations to be met.
- (3) The effect of displacement reduction enabled a vehicle with this engine to achieve 21 mpg U.S. combined label fuel economy, which is the best for that class of SUVs.

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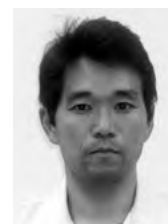
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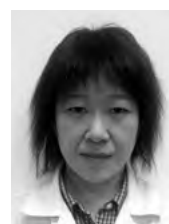
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