

New In-Line 4-Cylinder Gasoline Direct Injection Turbocharged Downsizing Engine

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ABSTRACT

Two new models of in-line four-cylinder VTEC turbo engine have been developed as part of the cluster of new-generation power train technologies known as EARTH DREAMS TECHNOLOGY, which achieves a high-level balance between driving performance and fuel consumption. Both VTEC engines use high-tumble ports, valve timing control (dual VTC) of both intake and exhaust camshafts, multi-hole direct side injectors, and high-response turbochargers with attached electric waste gate actuator. With these technologies in common, the new engines successfully yield maximum thermal efficiency and power through cooperative control and turbocharging conditions based on combustion technology that uses high-tumble flow. The 1.5 L engine puts out the same 110 kW of maximum power as the 2.0 L naturally aspirated engine while increasing low- and medium-speed torque by a maximum of 30%. A vehicle with this engine installed achieved fuel consumption of 17 km/L in JC08 mode, which puts it at the top of the minivan class, and a 75% reduction relative to the level required by Japanese 2005 regulations for exhaust emissions. As a high-powered sport engine, the 2.0 L model achieves maximum output of 228 kW and maximum torque of 400 Nm. A vehicle with this engine installed achieved CO₂ emissions of 170 g/km in European fuel economy mode and Euro 6b compliance.

1. Introduction

Target values for fuel economy regulations have been set to be met in developed countries in North America, Europe, and elsewhere from 2020 to 2025, and in developing countries by 2015. As a technology that achieves a balance between compliance with those fuel economy regulations and product competitiveness, the downsizing turbocharged engine is being developed by OEM manufacturers in Europe, in particular, and is being marketed in Europe, the United States, and China. Honda has also issued press releases announcing global marketing of VTEC TURBO variations that are part of the cluster of new-generation power train technologies known as EARTH DREAMS TECHNOLOGY, which achieve a balance of driving performance and fuel consumption. The VTEC turbo engine provides greater torque, and it can achieve dynamic performance matched to the vehicle class even with a smaller displacement than naturally aspirated (NA) engines. The reduction of engine friction also makes it possible to increase fuel economy.

This VTEC turbo engine is scheduled for global marketing, to include the Europe market, and it is

positioned as a world strategy engine intended to contribute to heightened fuel economy and increased product competitiveness. Figure 1 shows the EARTH DREAMS TECHNOLOGY line-up and the positioning of the two types of developed engine described herein.

This paper will introduce the applications of these technologies and the performance they achieve.

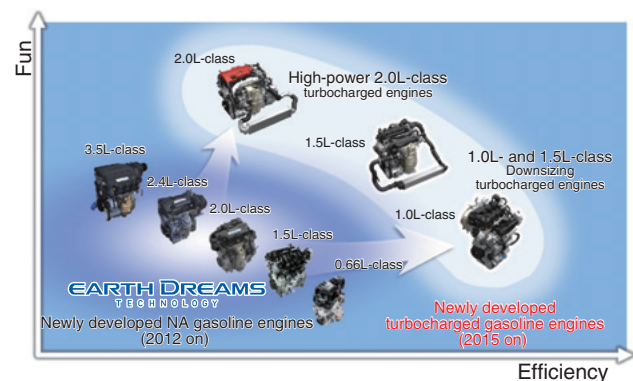


Fig. 1 EARTH DREAMS TECHNOLOGY

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2. Development Aims

The main aim of the downsizing turbocharged engine is to heighten fuel economy^{(1), (2)}. Reducing displacement and actively using the high-load range at low engine speeds can lower the proportion of torque required for driving that is engine friction, thereby heightening fuel economy. The tendency of torque in the range of actual use as it differs with different engine displacements is shown in Fig. 2(a) and the tendency of friction at normal engine speeds is likewise shown in Fig. 2(b). On the one hand, these tendencies suggest that when engine displacement is changed from 2.0 L to 1.5 L, friction can be expected to decrease by approximately 30%, and fuel economy to increase. On the other hand, an increase of approximately 35% or more in torque will be required in order to maintain the same level of practical performance. That is why the engine is combined with a highly efficient turbocharger that yields effective turbocharged pressure in the low engine speed range to produce that part of the power accounted for by the reduced displacement.

In order to be competitive on the downsizing turbocharger market where European OEM manufacturers have gone first, development was carried out with the aim of achieving the top category in its class by balancing fuel economy, power, emissions (EM), and cost.

The newly developed 1.5 L downsizing turbocharged engine was intended to replace 1.8 L to 2.0 L displacement class NA engines. A compact turbocharger that delivers good response with peak torque from low engine speeds was selected, and the aim of development was defined as

simultaneously achieving acceleration performance for ease of handling on city streets and top level power performance in its class together with low fuel consumption and low emissions.

The development objectives for the 1.5 L downsizing turbocharged engine were:

- (1) A balance of high power and high torque at low engine speeds
- (2) Low fuel consumption and low emissions at the top level in its class

The newly developed 2.0 L downsizing turbocharged engine, as a high-powered sport engine, was equipped with a large turbocharger. The aim of development was defined as achieving a balance between the world's highest speed for a front-engine, front-drive vehicle, based on lap times on the Nürburgring circuit, and excellent environmental performance.

The development objective for the 2.0 L downsizing turbocharged engine was to achieve a balance between the top class of per-liter power in the world and environmental performance.

3. Main Engine Specifications

The 1.5 L and 2.0 L VTEC turbo engines were made with the same bore pitch and other main specifications, and with the same block structure as the updated NA engine⁽³⁾. At the same time, the specifications were configured with the optimal combustion concept for turbocharged engines as the basis.

In a turbocharged engine, the rise in temperature of the compressed air-fuel mixture makes knocking more likely to occur, and even if the ignition timing is retarded for that reason because of the rapid combustion, it becomes important to obtain stable combustion. Therefore a high-tumble port was adopted to generate stronger tumble motion inside the cylinder and heighten the turbulent kinetic energy, and the piston crown was shaped so that the high tumble flow could be maintained until close to compression top dead center. The main combustion system was also configured with a multi-hole direct injector to form a homogeneous air-fuel mixture while limiting its adhesion to the surfaces of the piston and sleeve wall and with dual-VTC for optimal control of the scavenging effect and the amount of internal exhaust gas recirculation (EGR). Combining this with a high-response turbocharger achieved higher thermal efficiency and higher output.

The engines were matched to the requirements of the vehicles in which they are installed, and in the case of the 1.5 L type, the emphasis was placed on ease of handling on city streets and economy, and priority was therefore given to high low-speed torque and low fuel consumption. The 2.0 L turbocharged engine to be installed in the CIVIC TYPE R was configured with specifications to achieve maximum power performance

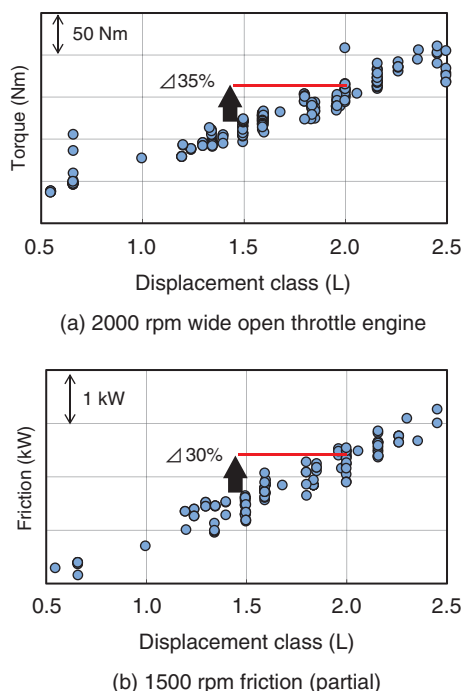


Fig. 2 Improved fuel efficiency by downsizing turbo

Table 1 Engine specifications

Engine type	1.5 L		2.0 L	
	Developed	BASE	Developed	BASE
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder	In-line 4-cylinder	In-line 4-cylinder
Bore x Stroke (mm)	73 x 89.4	73 x 89.4	86 x 85.9	86 x 86
Displacement (cm ³)	1496	1496	1996	1998
Aspiration	Turbocharged	Natural	Turbocharged	Natural
Turbin/Compressor diameter (mm)	37/46	no	47/58	
Crank journal diameter (mm)	46	46	55	55
Compression ratio	10.6	11.5	9.8	11.0
Valve train	DOHC In-Ex VTC	DOHC-VTEC In VTC	DOHC In-Ex VTC	DOHC VTEC In-Ex VTC
Number of valves	4 per cylinder	4 per cylinder	4 per cylinder	4 per cylinder
Valve diameter (mm)	28/23	29/25	35/29	35/30
Intake/exhaust				
Engine oil	0W-20	0W-20	0W-20	5W-30
Fuel injection type	DI	DI	DI	PI
Fuel	RON91	RON91	RON95	RON95
Maximum Power (kW/rpm)	130/5500	97/6600	228/6500	148/7800
Maximum Torque (Nm/rpm)	230/1600-5000	155/4600	400/2500-4000	193/5600
Maximum thermal efficiency (%)	38.0	34.8	36.6	-

while maintaining a high level of environmental performance as a high-powered sport engine. Table 1 shows the main specifications of the engines.

The 1.5 L type runs on regular gasoline but has a compression ratio of 10.6, and achieves a high level of environmental performance with maximum thermal efficiency of 38% together with maximum torque of 203 Nm from 1600 rpm for low-speed characteristics that are favorable for usability on city streets. The 2.0 L type was equipped with a larger turbocharger in order to realize the top class of per-liter power in the world with maximum power of 228 kW, while at the same time achieving a balance with high-level environmental performance with maximum thermal efficiency of 36.6%.

Figure 3 shows comparisons of each engine with the base NA engine in terms of power performance. The 1.5 L type was a replacement for the 2.0 L NA engine, but it has the same maximum power of 110 kW while yielding low and medium-speed torque that is a maximum of 30% higher. In the case of the 2.0 L turbocharged engine, the base NA engine for the CIVIC TYPE R is a 2.0 L engine, so heightened performance was achieved in all areas with power 50% higher at maximum and torque 100% higher.

The substance of the technology adopted in order to achieve the balance of power performance and environmental performance described to this point will be described below.

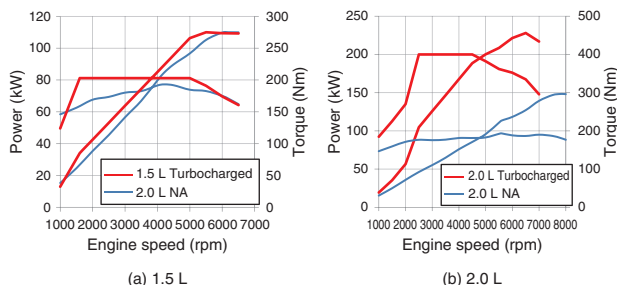


Fig. 3 Comparison of performance curve

4. Achieved Technology

4.1. Rapid Combustion Technology

In order to suppress knocking and enable high-load operation with a direct injection turbocharged engine, as well as to take steps to promote the evaporation of direct injected fuel and to make the air-fuel mixture homogeneous, and also to satisfy particulate matter (PM) regulations, it is important to strengthen the tumble motion inside the pipe. Ordinarily, tumble flow is strengthened by narrowing down the area of the intake port to increase the flow velocity inside the intake port, but this lowers the flow coefficient. Since the engine is also required to output power at high engine speeds, this requires enhancing the flow coefficient while maintaining the high-tumble flow. This optimization was carried out using CFD.

Figure 4 shows the differences in intake port and piston shape between the naturally aspirated and turbocharged 1.5 L engines.

The intake port lies closer to the horizontal than the angle of the port in the NA engine to realize an intake flow that follows the pentroof shape. The edge of the port at the bottom side (A in Fig. 4) is raised more toward the perpendicular, and this suppresses the opposing tumble flow inward from the opposite direction, limiting the lowering of the flow coefficient while realizing a high tumble ratio. Steps were then taken for rapid combustion by adopting a piston top with a shape that smoothly reverses the main tumble flow in the piston direction that occurs during the intake stroke and maintains the tumble flow until close to compression top dead center. Figure 5 shows the flow pattern in the cylinder at an engine speed of 1500 rpm and wide-open throttle as sought using CFD (VECTIS Ver. 3.12 from Ricardo). Figure 6 shows a comparison of the tumble ratio and turbulent kinetic energy.

A powerful flow in the direction of the piston was observed to form during the first half of the intake stroke (crank angle of 100 deg). This flow is reversed by the shallow-dish shape of the piston crown, forming a tumble flow. Tumble vortices observed during the compression stroke (crank angle of 270 deg) are flattened down into

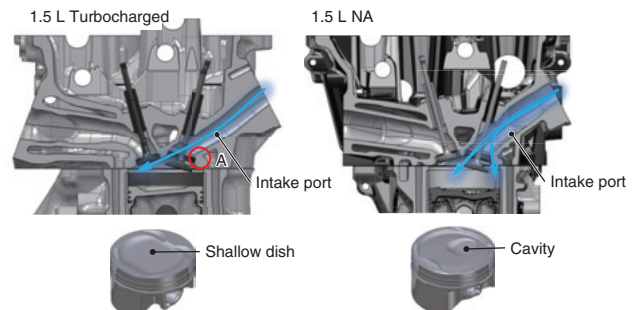


Fig. 4 Comparison of intake port and piston shape

the pentroof, are held there from 60 deg to 0 deg before top dead center, are converted into turbulent kinetic energy (turbulence), and promote flame propagation combustion. The turbulent kinetic energy near compression top dead center has approximately twice the value of the corresponding energy in an NA engine.

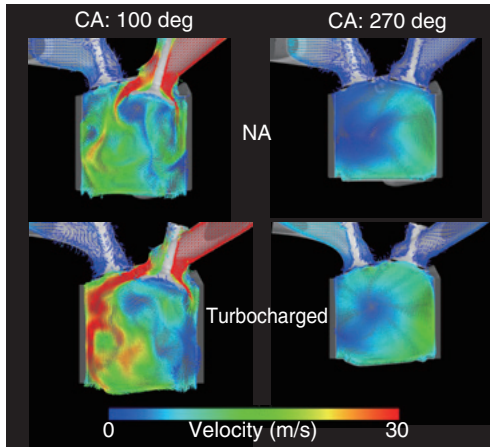


Fig. 5 In-cylinder flow pattern (1500 rpm motoring)

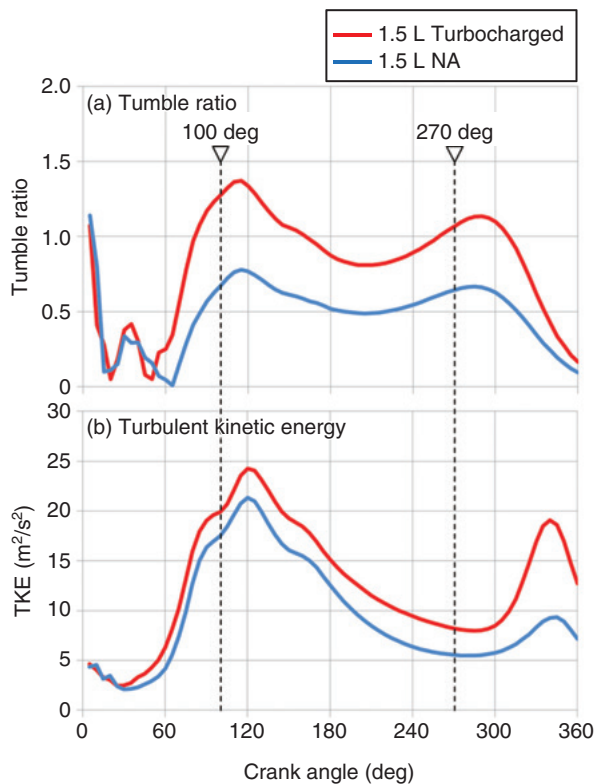


Fig. 6 In-cylinder flow pattern (1500 rpm motoring)

Table 2 Turbocharger specifications

		1.5 L	2.0 L
Turbocharger supplier		Mitsubishi	Mitsubishi
Turbine	Scroll	Mono	Mono
	Wheel Diameter/Vane	$\phi 37/11$	$\phi 47/11$
	Permissible speed	245000 rpm	195000 rpm
	Housing material	A3K (austenitic cast steel)	A3K (austenitic cast steel)
Compressor	Wheel Diameter/Vane	$\phi 46/6+6$	$\phi 58/6+6$
	Permissible speed	241000 rpm	191000 rpm
Waste gate	Actuator	Electronic	Electronic
	Valve diameter	$\phi 28$	$\phi 35$

4.2. Turbocharger Technology

Single-scroll-type turbochargers were adopted and their optimal specifications were chosen according to their performance targets.

A cylinder head with integrated exhaust port was adopted for highly efficient cooling of exhaust gases together with a turbine housing made of cast stainless steel for high heat resistance. The aim was to raise high-load fuel economy by expanding the range in which driving in stoichiometric mode is possible. This established specifications capable of withstanding exhaust gases at temperatures up to 950°C without relying on enriching the air-fuel ratio to lower the exhaust gas temperature, even when the exhaust gases are at high temperatures. A newly developed electric waste gate actuator (E-W/G ACT.) was adopted as a means for heightening fuel economy under low-load conditions.

Table 2 shows the turbocharger specifications for each engine, and Fig. 7 shows an external view of the turbocharger. The 1.5 L type was configured as a compact turbocharger that emphasizes high torque and response from low engine speeds. For the 2.0 L type, a size was chosen to provide flow volume that satisfies the requirement for 228 kW power output. The compressor

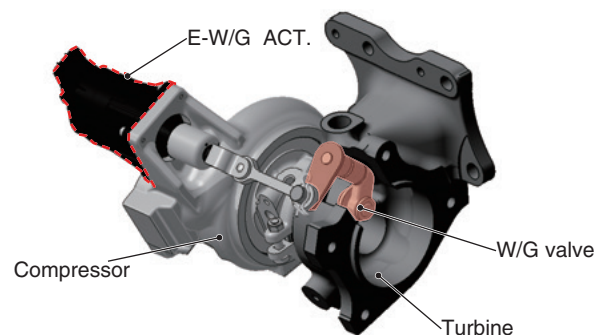


Fig. 7 Turbocharger assembly

map for the 1.5 L engine is shown in Fig. 8(a) and for the 2.0 L engine in Fig. 8(b). The compressors were adopted each with its own broad flow volume range characteristics, allowing for an extra margin in the surge limit and speed limit with regard to operation points.

Figure 9 shows the E-W/G ACT. The E-W/G ACT. has a screw lead system in the thrust transmission unit of the waste gate valve (W/G valve) to provide greater retention by means of friction. Consequently, it is capable of retention with a smaller holding current even when the exhaust pressure is high.

The adoption of an E-W/G ACT. made it possible to set up and control the optimal turbocharged pressure by making use of the degree of freedom in opening and closing the W/G valve [Fig. 10(a)]. In the NA range, the W/G valve is set wide open to limit the difference between the pressure in the exhaust manifold and the pressure after the turbine. The reduction in the exhaust pumping loss yielded greater fuel economy. Cooperative control of the intake throttle and W/G valve aperture also generated torque according to the vehicle demand, and when it is excessive, the intake throttle aperture and W/G valve aperture are controlled according to the target turbocharged pressure, enhancing response [Fig. 10(b)].

With the former, positive-pressure W/G valve, the

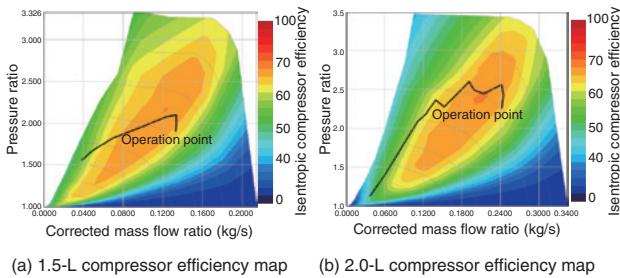


Fig. 8 Compressor efficiency map

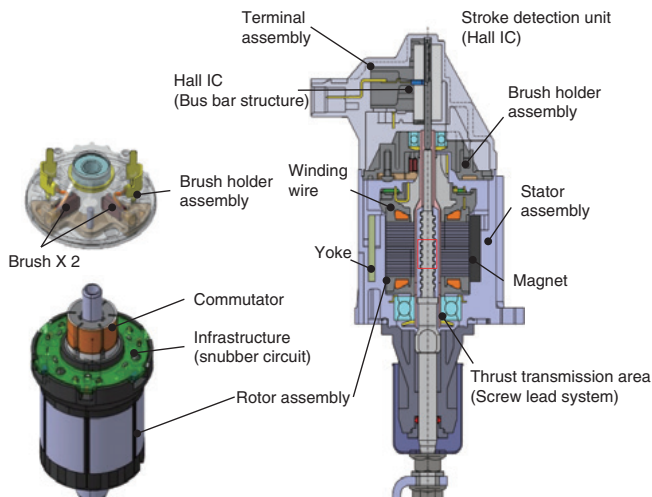


Fig. 9 E-W/G ACT.

valve could not be opened unless the intake pressure (PBA) matched or exceeded the W/G valve set pressure. Consequently, the valve could not be opened in the NA high engine speed range, where the PBA is close to atmospheric pressure. The turbocharger was therefore made to do unproductive work, causing exhaust pressure to rise and increasing the pumping loss. Here, the adoption of an E-W/G ACT. avoids this issue (Fig. 11).

Figure 12 shows the rate of decrease in brake specific fuel consumption (BSFC) due to adoption of

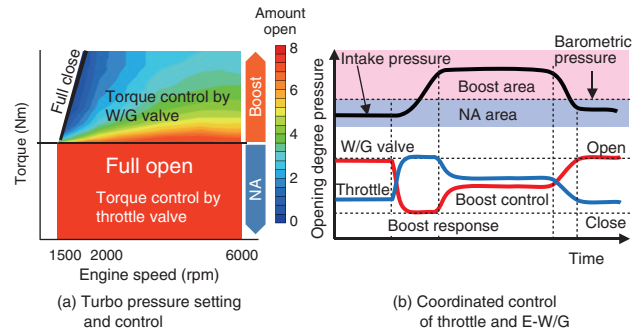


Fig. 10 Coordinated control

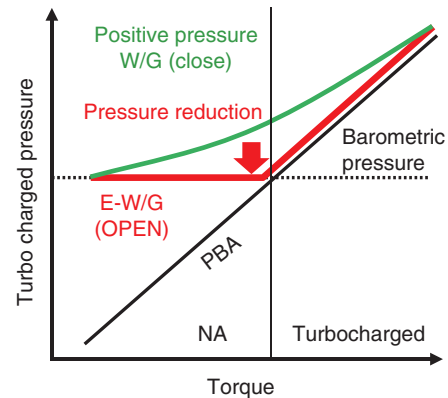


Fig. 11 Comparison of W/G valve specification

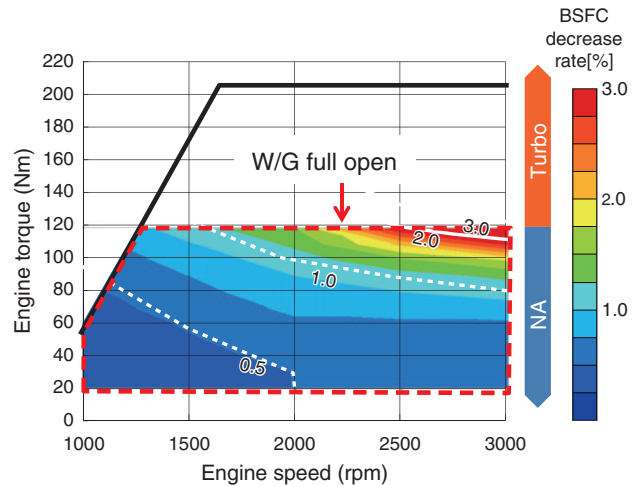


Fig. 12 BSFC decrease map

the E-W/G ACT. In the NA range, the positive impact on BSFC becomes greater on the higher engine speed side, where the exhaust flow increases, reaching a maximum of 3.0%.

4.3. Dual VTC Technology

Dual VTC was adopted for the 1.5 L type while the 2.0 L type additionally adopted VTEC on the exhaust side. Figure 13 shows some typical operating regions, and the following describes the use of valve timing control in these regions.

4.3.1. Low engine speed, high-load range

The region shown as (1) in Fig. 13 contributes greatly to response when a vehicle starts moving from a stop, and it requires greater low-speed torque. It is effective in that case to take advantage of the scavenging effect that uses the unique turbocharger condition in which the intake pressure is higher than the exhaust pressure. When the intake and exhaust valve overlaps are set larger under conditions where intake pressure is relatively high, the residual gas in the cylinder is scavenged to the exhaust system, and this can raise charging efficiency and suppress knocking (area (a) in Fig. 14).

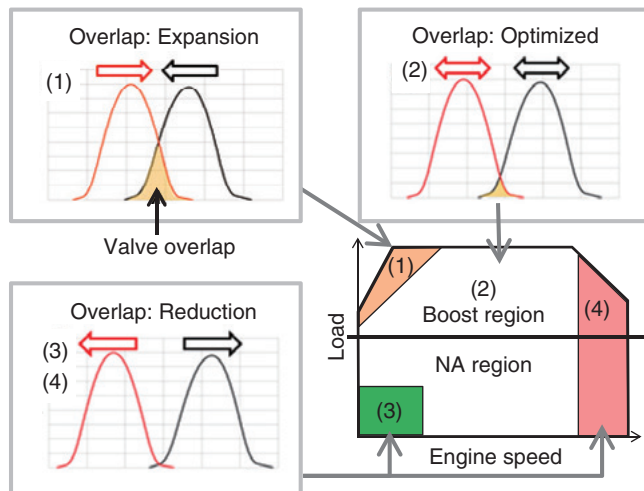


Fig. 13 Dual-VTC strategy

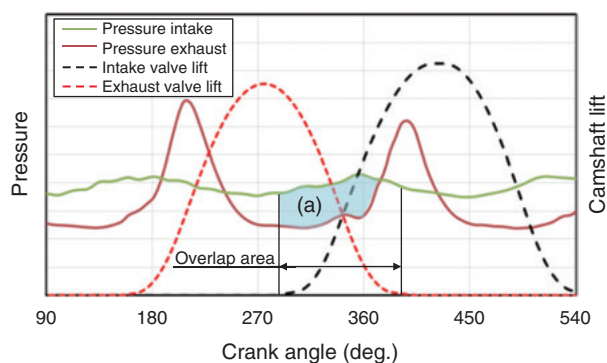


Fig. 14 Intake, exhaust pressure and scavenging area

At the same time, the increased gas flow due to scavenging can increase the turbine speed, yielding a 30% increase in torque at 1500 rpm relative to the 2.0 L NA engine.

Figure 15 shows a comparison of the pressure diagrams for the 2.0 L NA base engine and the 1.5 L turbocharged engine under full load at 1500 rpm. The decrease in stroke volume caused by downsizing is compensated for by the turbocharged pressure, so that high pressure is generated in a small stroke volume. The ignition timing is retarded in order to avoid the knocking due to increased pressure from turbocharging, but the rapid combustion produces a higher rate of heat release, which enables a higher indicated mean effective pressure (IMEP).

4.3.2. Medium engine speed range

In the medium to high engine speed range shown in graph (2) in Fig. 13, gradually reducing the overlap limits the increase in residual gas that accompanies increased exhaust pressure. When driving under acceleration, immediately controlling the electric waste gate valve to close completely makes it possible to raise the turbocharged pressure effectively.

4.3.3. Low vehicle speed and low engine speed range and high power range

In the low vehicle speed and low engine speed range shown in graph (3) in Fig. 13, the overlaps are reduced in order to heighten combustion stability by reducing the internal EGR amount as well as to lower exhaust resistance in the high-speed range at (4) and heighten knocking resistance.

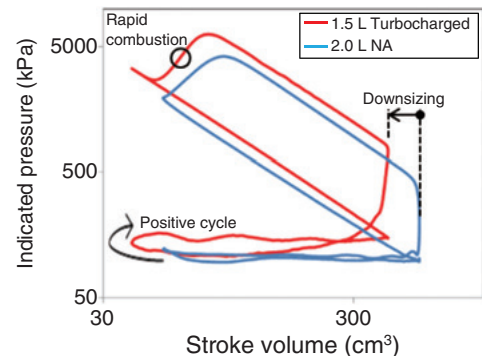


Fig. 15 Comparison of P-V diagram (1500 rpm WOT)

5. Fuel Consumption and Emissions

5.1. Fuel Consumption

Figure 16 shows the separate fuel consumption characteristics of each engine. The 1.5 L engine achieves the lowest BSFC of 220 g/kWh, and the 2.0 L engine achieves the lowest BSFC of 230 g/kWh. Comparison

with the separate fuel consumption characteristics of the 2.0 L NA engine, shown for reference at (b) in the figure, indicates not only that both the 1.5 L and 2.0 L engines have more favorable maximum efficiency point values, but that they have a broader range of higher efficiency.

The downsizing turbocharged engine can make active use of low engine speed and high-load operation. Therefore it is important to reduce fuel consumption in this range. Taking the 1.5 L engine as an example, Fig. 17 shows the breakdown of BSFC reduction under full load at 1500 rpm compared to the 2.0 L NA engine. In the case of the NA engine, the air-fuel ratio is set richer in order to increase power at wide-open throttle, and this avoids knocking. The downsizing turbocharged engine, on the other hand, increases its knocking resistance by means of rapid combustion and the scavenging effect, and therefore it can be operated stoichiometrically. Stoichiometric operation contributes 75% of the BSFC reduction effects, which is larger than cooling loss and pumping loss at 24% and friction reduction at 1%. Control of the internal EGR amount by dual VTC and stable combustion by means of a high-tumble flow also reduce pumping loss and yield lower fuel consumption across a wide load range up to the medium-load range. A 2015 model STEPWGN with this engine installed achieved fuel consumption of 17 km/L in JC08 mode, which puts it at the top of the minivan class. By means of similar technology, a vehicle with the 2.0 L engine installed achieved CO₂ emissions of 170 g/km in European fuel economy mode.

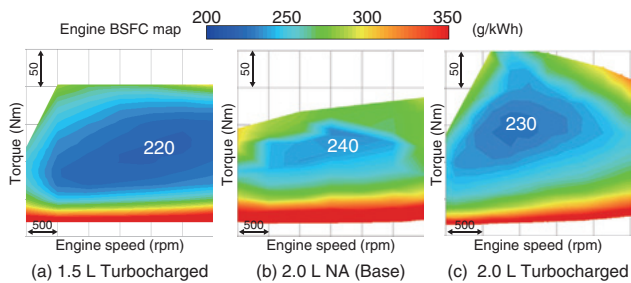


Fig. 16 Comparison of BSFC maps

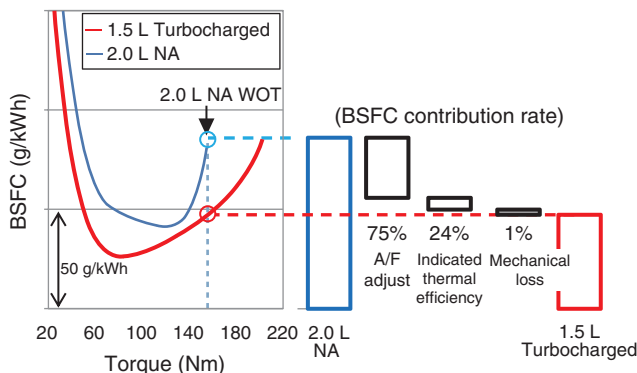
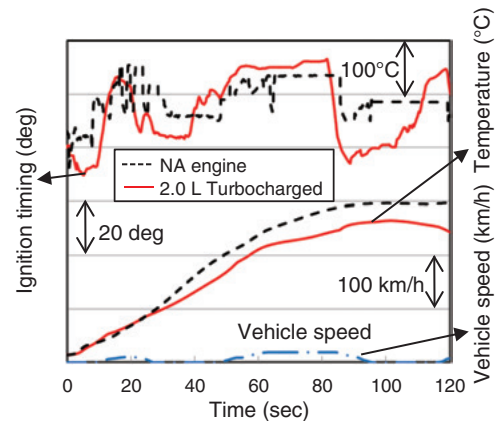


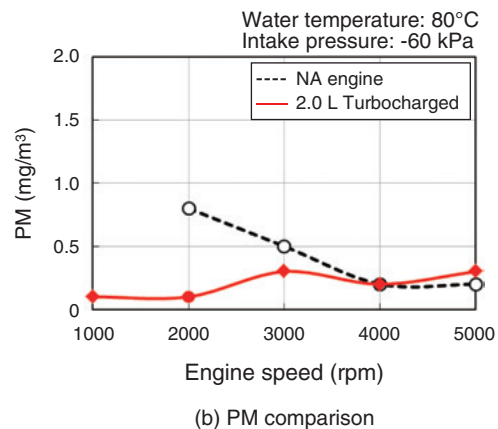
Fig. 17 Breakdown of BSFC reduction (1500 rpm WOT)

5.2. Low Emissions

In catalyst warm-up mode in a turbocharged engine, the increased heat mass due to the turbocharger becomes an issue. By contrast, the higher combustion stability gained by the use of a high-tumble port makes it possible to enlarge the valve overlap to introduce hot internal EGR into the combustion chamber, and this yields promotion of fuel evaporation. The ignition timing can also be retarded by comparison with the NA engine, making it possible to achieve a rise in catalyst temperature sufficient for application of Euro 6b [Fig. 18(a)]. With regard to soot emission performance after the engine is completely warmed up, the high-tumble flow and fuel injection pressure of 20 MPa together with optimal injection timing also successfully reduce the adhesion of fuel in the cylinder. Figure 18(b) shows measurement data for the 2.0 L engine. This engine achieved Euro 6b compliance by soot emission performance equal to or better than a mass-production direct injection NA engine. Using similar technology, the 1.5 L engine achieved a 75% reduction relative to the level required by Japanese 2005 regulations for exhaust emissions.



(a) Catalytic activity temperature comparison



(b) PM comparison

Fig. 18 Emission measurement data

6. Conclusion

A turbocharged downsizing engine employing a wide-range turbocharger with electric waste gate actuator, dual VTC, multi-hole direct side injector, and high-tumble port producing high-tumble flow was developed and obtained the following results.

- (1) The 1.5 L engine raised low and medium-speed torque by a maximum of 30% relative to the 2.0 L NA engine while maintaining maximum power of 110 kW. A vehicle with this engine installed achieved fuel consumption of 17 km/L in JC08 mode, which puts it at the top of the minivan class, and a 75% reduction relative to the level required by Japanese 2005 regulations for exhaust emissions.
- (2) As a high-powered sport engine, the 2.0 L engine achieved maximum output of 228 kW and maximum torque of 400 Nm. A vehicle with this engine installed achieved CO₂ emissions of 170 g/km in European fuel economy mode and Euro 6b compliance.

References

- (1) Petitjean, D., Bernardini, L., Middlemass, C., Shahed, S. M.: Advanced Gasoline Engine Turbocharging Technology for Fuel economy Improvements, SAE Technical Paper, 2004-01-0988, (2004)
- (2) Shahed, S. M., Bauer, K.: Parametric Studies of the Impact of Turbocharging on Gasoline Engine Downsizing, SAE Technical Paper, 2009-01-1472, (2009)
- (3) Suzuki, M., Hayakawa, S., Ishihaya, Y., Shindo, T.: Development of the New L4 Gasoline Engine for Compact Cars, JSAE Annual Congress Proceedings, No. 91-14, p.9-12, (2014)

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