

Development of New 3.5 L V6 Turbocharged Gasoline Engine for New NSX

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ABSTRACT

The concept for Honda's new NSX was to balance power performance achieving a high level of dynamic performance with a level of environmental performance meeting the demands of the times. A 3.5 L V6 turbocharged gasoline engine with a new frame was developed to realize this concept. In order to balance high power and high thermal efficiency, combustion was optimized through the use of in-cylinder direct injection and high-tumble ports, and the engine applies a twin turbocharger system featuring independent turbochargers positioned on the left and right banks and a fuel supply system combining in-cylinder direct injection and port injection. The powertrain was reduced in size and weight and given a low center of gravity in order to enhance vehicle dynamic performance. In addition, in response to the higher power of the engine, Fe spray-coated cylinder bores, a dry sump lubrication system, a three-piece water jacket, a swing arm valve train, and reduction chain drive were applied in order to help ensure cooling performance and frame reliability suited to the demands of sports driving.

As a result, the new engine achieves a maximum power of 373 kW (500 HP) and a maximum torque of 550 Nm across a wide range from 2000 rpm to 6000 rpm, in addition to complying with the European Euro6b and US ULEV125 regulations.

1. Introduction

Honda commenced mass production of the new model NSX in North America in 2016. The new NSX is a super sports model that inherits the concept of high dynamic performance balanced with high steering stability embodied in the first-generation NSX, which appeared in 1990.

The lightweight body of the new NSX is realized using innovative compound materials. The vehicle is provided with a 3.5 L V6 turbocharged gasoline engine positioned midship in a longitudinal layout behind the cockpit, and a three-motor hybrid system.

The 3.5 L V6 turbocharged gasoline engine for the new NSX, which will be discussed in this paper, is part of a direct-injection turbocharged gasoline engine series developed by Honda to balance environmental performance and the fun of driving (Fig. 1), but stands

out as having been developed with a particular focus on the fun of driving.

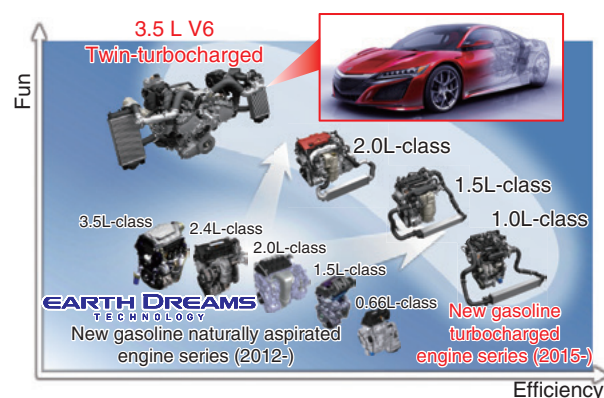


Fig. 1 Honda's series of direct injection turbocharged engines

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2. Development Aims

The concept for the new NSX was to balance power performance achieving a high level of dynamic performance with a level of environmental performance meeting the demands of the times (fuel efficiency, reduction of CO₂ emissions, compliance with exhaust gas regulations). In order to achieve a high level of steering stability, a compact engine frame able to be fitted longitudinally in a low-center-of-gravity position in the center of the vehicle would also be necessary. At the same time, it would be necessary to attempt to ensure the reliability of the engine under the high-load and high-acceleration conditions of sports driving. A 3.5 L V6 turbocharged gasoline engine was newly developed in order to satisfy these demands. The main development aims were as follows:

- (1) To balance the achievement of a maximum power of 373 kW (500 HP) and a maximum torque of 550 Nm with compliance with exhaust gas regulations in each country in which the vehicle would be sold (EU: Euro6b; US: ULEV125); and
- (2) To achieve a lightweight and compact frame suited to the rigors of sports driving.

3. Main Engine Specifications

Table 1 compares the specifications of the 3.5 L V6 turbocharged gasoline engine for the new NSX and a Honda mass production 3.5 L V6 naturally aspirated engine. The frame of the turbocharged gasoline engine applied in the new NSX has been modified against the naturally aspirated engine. In addition, turbochargers have been fitted in the left and right banks in order to increase power and efficiency. The combustion system incorporates high-tumble ports, a DI+PI fuel supply system that combines in-cylinder direct injection (DI) with port injection (PI), and hydraulic VTC (Dual-VTC) in the intake and exhaust valve train systems.

Figure 2 shows the exterior of the engine, and Fig. 3 shows the layout for mounting in the vehicle. By applying a dry-sump lubrication system and setting the V-bank angle at 75°, it has been possible to realize a low center of gravity and packaging that reduces the necessary space for the engine, both important factors in enhancing driving performance.

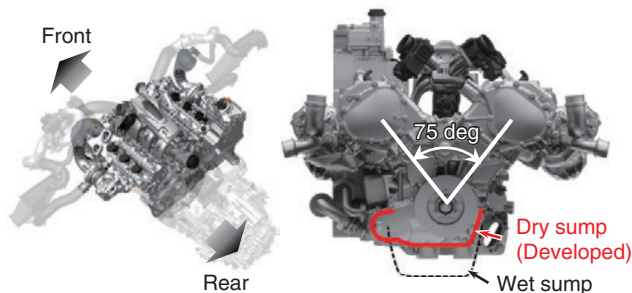


Fig. 2 Overall view of engine

Table 1 Engine specifications

Engine type	Developed JNC1	Previous JNB1
Cylinder configuration	V6-cylinder	V6-cylinder
Bore × Stroke (mm)	91.0 × 89.5	89.0 × 93.0
Displacement (cm ³)	3493	3471
Intake system	Turbocharged	Naturally aspirated
Bank angle (deg)	75	60
Lubrication system	Dry sump	Wet sump
Crank journal diameter (mm)	72	72
Compression ratio	10.0	11.5
Valve train	DOHC Hydraulic VTC (Intake/Exhaust)	SOHC VTEC/VCM
Number of valves	4 per cylinder	4 per cylinder
Fuel injection type	DI+PI	DI
Maximum power (kW/rpm)	373/6500-7500	231/6500
Maximum torque (Nm/rpm)	550/2000-6000	371/4700

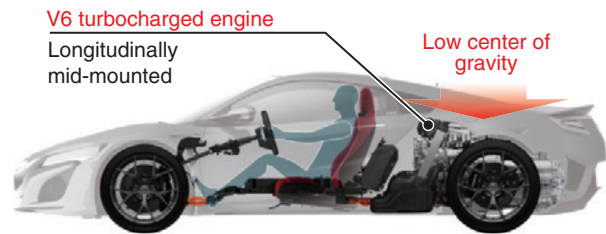


Fig. 3 Vehicle mounting layout

4. Engine Frame Technologies

In order to increase dynamic performance, the development sought to make the engine unit lighter and more compact. This section will introduce the main engine frame technologies applied in the new engine in order to also balance cooling performance, in response to the increased generation of heat resulting from the engine's increased power, with the realization of an engine frame that would be reliable under sports driving conditions.

4.1. Fe Spray-coated Cylinder Bores

A cylinder bore surface treatment using an Fe spray coating has been applied in the new engine in order to balance cooling performance in response to the engine's increased power with a lightweight and compact engine unit (Fig. 4).

In order to enhance cooling performance, cooling water channels have been positioned between the cylinder bores. Because it was necessary to realize a wall thickness on both sides that satisfies casting conditions when forming the cooling water channels, their use would increase the bore pitch, increasing the total length of the engine and

creating issues in terms of engine layout. The use of conventional iron cylinder sleeves (with a wall thickness of approximately 2.5 mm) would make the increase in bore pitch unavoidable. The use of Fe spray coating substituted the section corresponding to the sleeve with a thin 0.2 mm film that made it possible to control the bore pitch to 11 mm and position the cooling water channels in bore bridges. In addition, reducing the wall thickness of the iron increased thermal conductivity by 52% [Fig. 5(a)] and a weight reduction by 11% [Fig. 5(b)] against a conventional iron sleeve, making it possible to realize a lightweight and compact cylinder block.

In applying Fe spray coating, it is necessary to ensure the bond strength of the spray coating film. Broadly classifying the bond force of Fe and Al in the spray coating film, the forces at work can be categorized as follows. It is important to manage the area and the roughness of the spray-coated surface in relation to these forces:

- (1) Residual compressive stress in the spray coating Fe;
- (2) Mechanical bond force due to the base roughness of the sprayed surface (anchor effect); and
- (3) Intramolecular bond force at the boundary with the spray coating film.

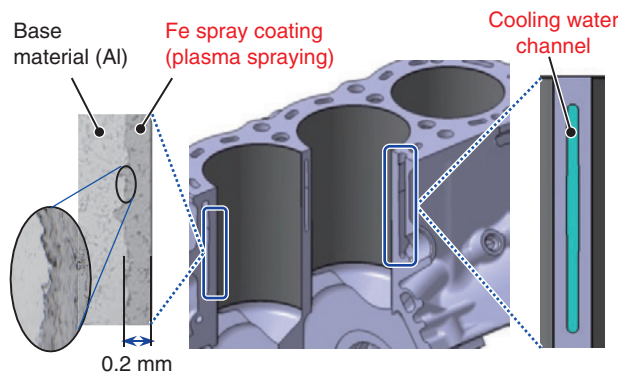


Fig. 4 Fe spray coating film and cooling water channels

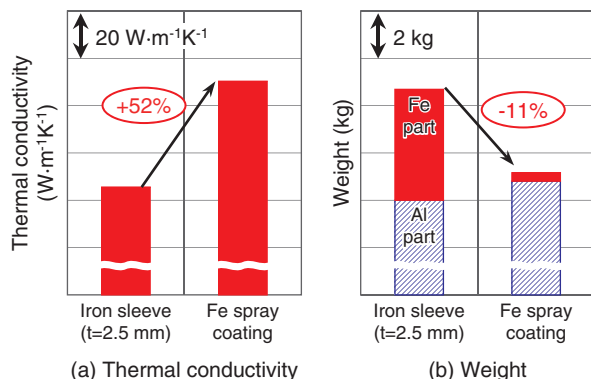


Fig. 5 Performance of Fe spray coating

Shot-blasting is utilized for base surface activation in the new engine. The base surface roughness was adjusted by changing the blast media size, and surface activation conditions that realized the desired bond strength were selected.

It was possible to realize the target bond strength by specifying the size of the blast media used in shot-blasting and managing surface roughness to within the range shown in Fig. 6.

As a result, the Fe spray coating displayed no peeling in durability tests using an engine dynamometer, achieving cylinder bores that displayed good cooling performance and contributed to the reduction of weight and size and the reliability of the engine frame.

4.2. Dry Sump Lubrication System

A dry sump lubrication system has been applied in the new engine in order to enhance dynamic performance and help ensure engine lubrication performance in severe driving environments.

Figure 7 shows an image of the entire dry sump lubrication system. In conventional wet sump lubrication, an oil pan and oil pump are positioned at the bottom of the

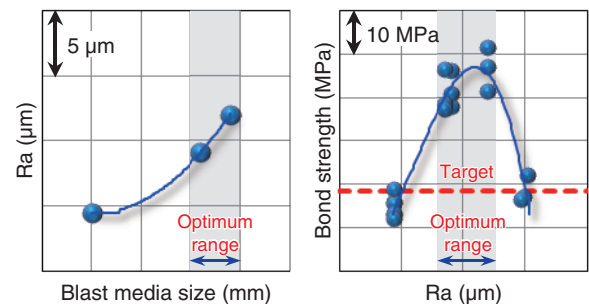


Fig. 6 Bond strength results

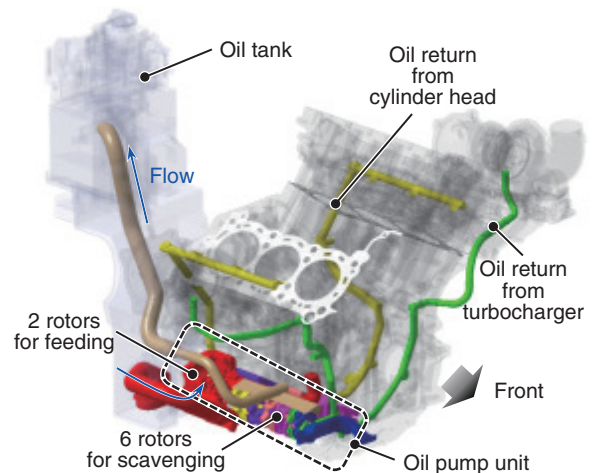


Fig. 7 Layout of dry sump lubrication system

engine. However, dry sump systems position an oil pump and oil tank separate to the engine, making it possible to reduce the mounting height of the engine by approximately 60 mm, thereby enhancing dynamic performance through the realization of a low center of gravity.

The use of an integrated structure in which the oil pump unit is positioned at the lower right of the engine and a feed pump and scavenge pump are positioned on the same shaft, in addition to increasing the speed of pump rotation and reducing the rotor diameter, has enabled a more compact lubrication system. Furthermore, offsetting the phase of each rotor (Fig. 8) has controlled pressure pulsations when oil is being discharged and reduced pump drive torque.

In a dry sump lubrication system, oil and blow-by gas are collected simultaneously from the crank chamber and the cam chamber by a scavenge pump, causing a high aeration rate in the oil returned to the oil tank. Because the supply of oil with a high aeration rate produces lubrication issues, it is important to control aeration. For the new engine, the gas separation performance inside the oil tank was increased, while the flow ratio of the feed pump and the scavenge pump was also optimized⁽¹⁾.

A cylinder known as a swirl pot is used for gas separation inside the oil tank. Oil sent from the scavenge pump is introduced to the swirl pot, where it is rotated, following the walls. The effect of centrifugal force promotes gas separation, while also controlling the trapping of air when the oil enters the surface of the liquid by reducing flow speed (Fig. 9). Because factors including the internal diameter of the swirl pot, the area of its opening, and the angle of introduction of the oil affect gas separation performance, analyses were conducted using CFD, and a swirl pot shape able to control aeration at the oil inlet was selected.

The longitudinal configuration shown in Fig. 10 was applied for the oil tank, and the oil amount was set between 4 L and 5 L. Under body acceleration conditions projected for sports driving around a circuit (cornering: 17.7 m/s^2 ;

accelerating: 9.8 m/s^2 ; decelerating: 11.8 m/s^2) and with 1.0 L of oil in the oil tank, the oil inlet shown as Area (a) in Fig. 10 is not exposed, and stable supply is ensured. In addition, under the same conditions, even with an oil amount of 5.0 L, oil does not reach the breather chamber positioned at the top of the oil tank, indicated by Area (b) in Fig. 10.

As a result, good lubrication performance has been achieved, with no issues such as declines in oil pressure due to oil intake issues or oil consumption due to oil infiltration into the breather chamber or the intake side, even during sports driving on a circuit.

4.3. Cooling System

Because increased power also increases heat rejection by the engine, it is important to reduce temperature, particularly that of the walls of the combustion chamber and of the

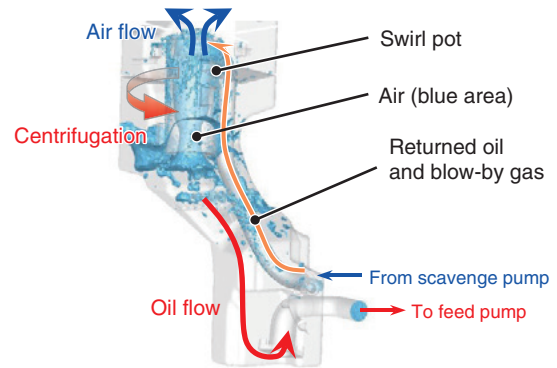


Fig. 9 Visualization of air separation in oil tank

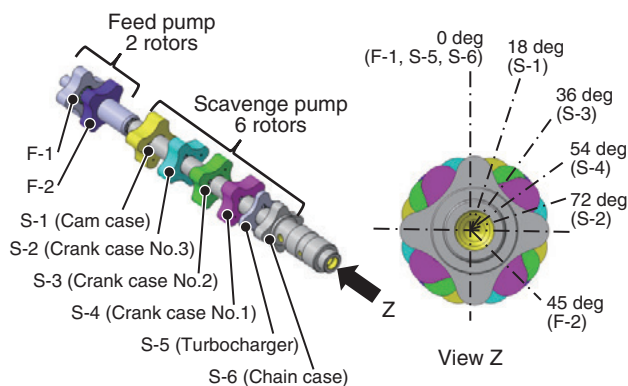


Fig. 8 Oil pump rotors

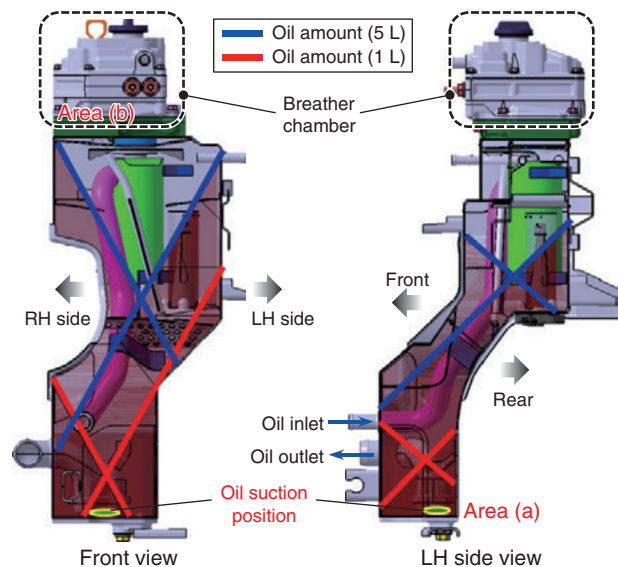


Fig. 10 Oil tank shape and oil level

exhaust gas. A three-piece water jacket configuration⁽²⁾ (Fig. 11) in the new engine increases reliability and controls knocking. This configuration actively cools the combustion chamber and the area around the exhaust ports.

CFD was utilized in studying the cooling water channels in order to analyze the distribution of cooling water flow speed and the temperature of each area of the cylinder heads and allow optimization of the shape of the water jacket. Figure 12 shows the results of study of the flow speed distribution of the cooling water. The use of a shape for the cooling water channels that controls peeling and stagnation of the flow and actively sends cooling water to the combustion chamber and the area around the exhaust ports, which have a high thermal load, has realized efficient cooling.

The use of a three-piece water jacket has expanded the area for heat conduction and optimized water flow, increasing heat rejection by approximately 14% against a conventional naturally aspirated 3.5 L V6 engine. In addition, the reduction of the temperature of the cylinder

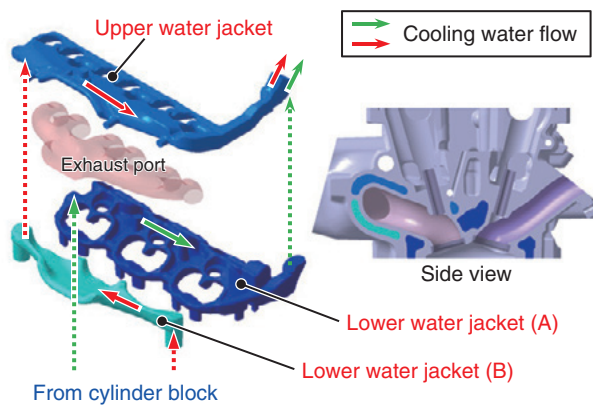


Fig. 11 3-piece water jacket

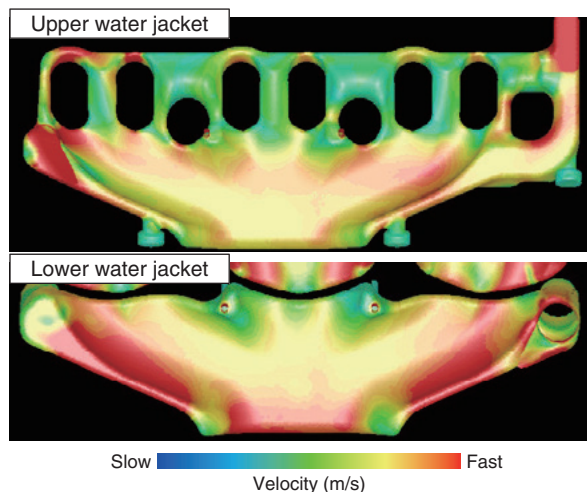


Fig. 12 Visualization of cooling water flow

heads has reduced the incidence of heat stress, contributing to the reduction of the size and weight of the engine.

4.4. Valve Train

A swing-arm valve train was adopted in order to reduce the size and weight of the engine unit (Fig. 13). This made it possible to realize compact cylinder heads, reducing the cross-sectional ratio of the cylinder heads by approximately 17% against a Honda mass-production 2.0 L in-line 4-cylinder turbocharged gasoline engine (DOHC), and realizing the same cylinder head size as a 3.5 L V6 naturally aspirated engine (SOHC). This also contributed to increasing the ability to fit the cylinder heads within the vehicle layout, making it possible to increase the angle of the V-bank to 75° within the limited space available and to position turbochargers on both sides of the engine.

4.5. Valve Timing Drive Method

Chain drive was adopted as the valve timing drive method in order to increase reliability in relation to the loads produced and to make the engine more compact. Figure 14 shows the chain drive system, in which three chains drive the cams on both banks via a reduction chain.

CAE was used in studying the drive layout, and the load

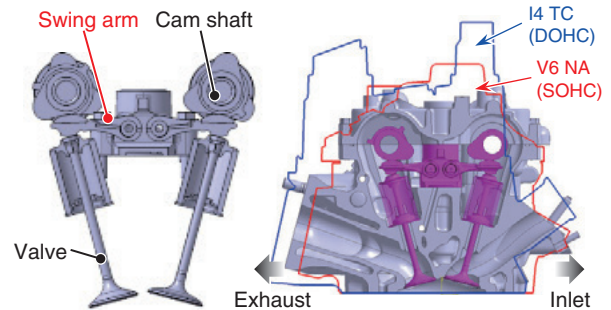


Fig. 13 Cylinder head layout

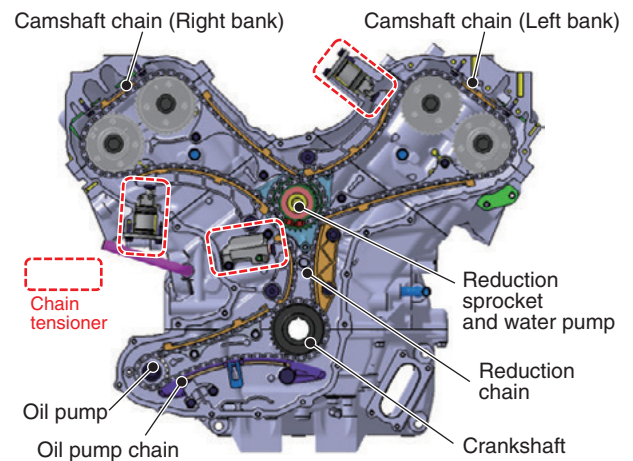


Fig. 14 Layout of reduction chain drive system

characteristic on the chains was compared for configurations using different numbers of chains (Fig. 15). It was observed that at some point, the load increases due to resonance with any number of chains. However, the three-chain system showed the desirable outcomes as it generated the least load by synthesizing the left and right bank cam drive torque via a reduction sprocket (an intermediate shaft), reducing the amplitude of torque transmitted to the reduction chain.

In addition, because the reduction chain is greatly affected by fluctuations in the angular velocity of the crankshaft, the chain tensioner relief pressure was optimized. The loads on the chain and tensioner displacement are in a trade-off relationship with relief pressure. Given this, relief pressure was set to enable control of tensioner displacement within an acceptable range of chain load (Fig. 16).

The positioning of the water pump on the same shaft as the reduction sprocket also increased the compactness of the layout of the auxiliary components.

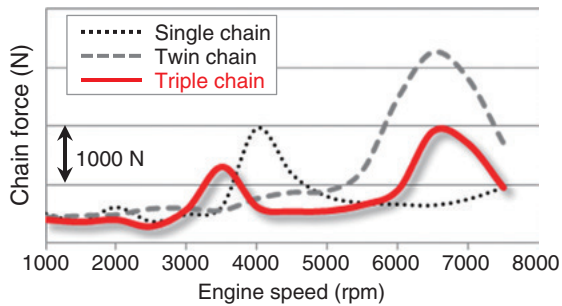


Fig. 15 Results of analysis of chain force

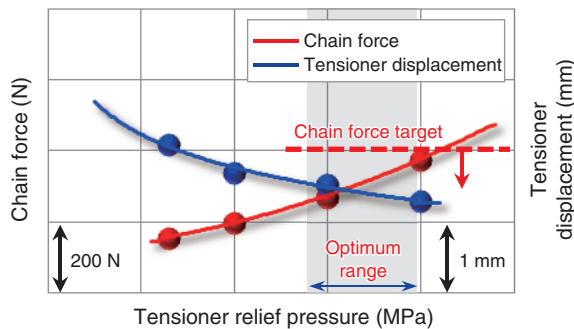


Fig. 16 Results of study of chain tensioner

5. Combustion Technologies

In order to balance high power and high thermal efficiency with low emissions, the combustion system of the new engine applies technologies to realize rapid and stable combustion: DI using multi-hole injectors and high-

tumble intake ports^{(2), (3)}. These technologies have enhanced both combustion and emissions performance. In addition, in order to increase power, the engine uses a twin turbocharger system (independent turbochargers on the right and left banks) and a DI+PI fuel injection system. This section will introduce these technologies.

5.1. High-tumble Intake Port

The use of high-tumble intake ports promotes the mixture of fuel and air and increases turbulent kinetic energy around the top dead center in the compression stroke, enabling rapid and stable combustion.

Figure 17 shows the shape of the intake ports in the new engine, while Fig. 18 shows the results of actual measurements of the tumble ratio. The intake ports produce a high-tumble flow displaying a tumble ratio two times or more that of a conventional 3.5 L V6 naturally aspirated engine across the entire range of valve lift, contributing to the realization of increased combustion stability.

5.2. Turbocharging Technologies

The new engine employs monoscroll turbochargers with electronic wastegates in order to increase power and enhance responsiveness. The use of a twin turbocharger system that positions turbochargers on each of the banks has enabled both an efficient longitudinal layout of the midship V engine, as well as exhaust interference control through the three-cylinder-per-side configuration. In the process of turbocharger selection, one-dimensional simulations were

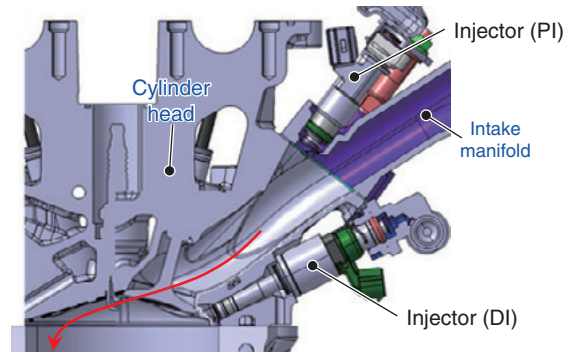


Fig. 17 Intake port layout

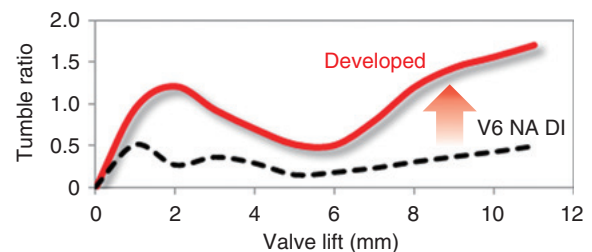


Fig. 18 Results of measurements of tumble ratio

used to study performance during operation at wide-open throttle. Turbocharger size results in a trade-off between low-speed torque and maximum power performance. For the new engine, small turbochargers able to achieve the target power were selected, and a balance was achieved between high power and high torque (Fig. 19). The turbochargers are directly mounted on the cylinder heads, thereby reducing the length of the pipes from the exhaust ports to the turbine and enhancing turbo response.

A high-efficiency air-cooling intercooler is positioned on the intake side, directly beside the engine (Fig. 20). Reducing the length of the turbocharger pipes from the compressor to the throttle reduces intake pressure loss, enhancing turbo response.

5.3. DI+PI Fuel Supply System

A DI+PI fuel supply system has been adopted in the new engine in order to provide a fuel supply system able to cope with the increased volume of fuel flow with higher engine power.

Increasing the size of a DI injector in order to increase the fuel supply presents an issue in adequately controlling the injection amount when the required amount of fuel is very small, for example when the vehicle is idling at high altitudes where the air density is low or in high-temperature

environments. In the new engine, the fuel flow range of the DI injector is the same as that in a conventional naturally aspirated engine. The DI injector satisfies the demands of fuel flow rate control on the low-flow-rate side, and is supplemented by PI during high-load driving, realizing a wide range of fuel flow rates.

The operation of DI and PI was comprehensively judged from the perspectives of combustion stability, brake specific fuel consumption (BSFC), and emissions, and was set as shown in Fig. 21.

(1) Low engine speed/high-load area

In this area, the turbocharger scavenges using Dual-VTC. DI is used in this area in order to help prevent fuel being blown to the exhaust system.

(2) High engine speed/high-load area

DI is supplemented by PI in this area in order to realize the demanded fuel flow.

(3) Partial area

To establish the partial area, the effect of the injection ratio between DI and PI was determined based on engine dynamometer testing with the results shown in Fig. 22. In a DI engine, it can occur that the vaporization and mixture of the fuel does not proceed in the low engine speed, low-load range in which the tumble flow is weak, and combustion stability declines. Combustion design for the new engine was conducted with DI as the basis, and port shapes were selected to generate a strong tumble flow even at low loads.

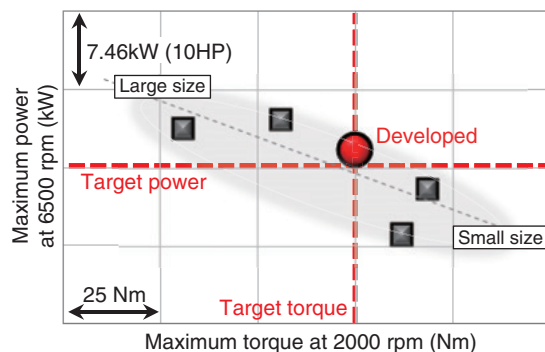


Fig. 19 Relationship between low-speed torque and maximum power

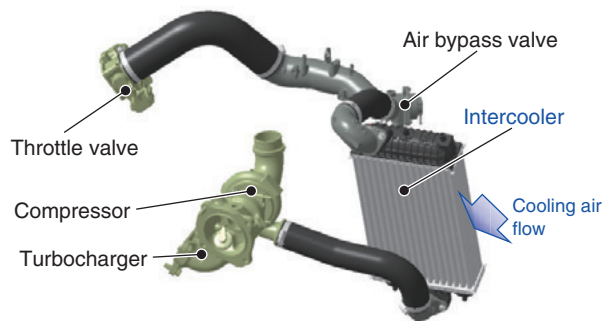


Fig. 20 Layout of turbocharger and cooling system

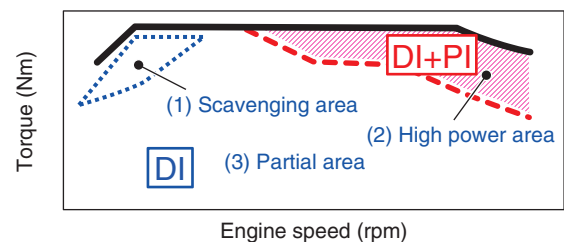


Fig. 21 DI+PI fuel injection system operation

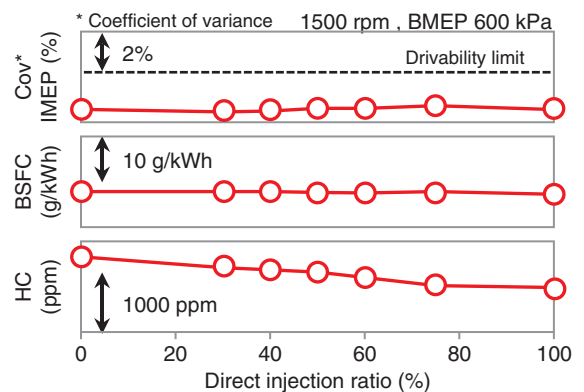


Fig. 22 Combustion characteristics by direct injection ratio

Because of this, combustion stability and BSFC do not change in response to the injection ratio between DI and PI, and rapid and stable combustion is ensured by a strong tumble flow, allowing the engine to achieve good combustion under all conditions. The PI spray has been set pointing downwards in order to control the adhesion of fuel sprayed by the PI system to the sleeve due to strong tumble motion at high loads. Because of this, a higher volume of fuel adheres to the undersides of the ports during PI at low loads. As a result, DI is superior from the perspective of hydrocarbons (HC) in the exhaust gas. Based on this result, DI only is used in the partial area.

This mode of operation has created a system that realizes optimal fuel supply throughout the entire driving range.

6. Achieved Engine Performance

6.1. Power Performance

Figure 23 shows the power and torque characteristics of the new engine.

The engine's maximum power of 373 kW (500 HP) is produced from 6500 rpm to 7500 rpm in the red zone. Maximum torque of 550 Nm is produced from 2000 rpm to 6000 rpm.

Using automotive performance design technologies, the engine power target was determined with consideration given to the power provided from the 3-motor hybrid system in order to achieve the overall vehicle dynamic performance target. In addition, the achievement of flat torque in the medium engine speed range offers a smooth acceleration characteristic with no feeling of inconsistency as engine speed increases.

The system overall achieves a maximum power of 427 kW (573 HP) and a maximum torque of 646 Nm, a level of power performance suited to the new NSX.

6.2. Fuel Efficiency Performance

The fuel efficiency of the new engine has been increased by rapid and stable combustion enabled through DI and high-tumble ports, and internal EGR achieved through Dual-VTC. In addition, knocking has been controlled by enhancing cooling performance in the area around the combustion chamber via the use of Fe spray-coated cylinder bores, pistons provided with cooling channels, and efficiently cooled cylinder heads, enabling a compression ratio of 10.0. As a result, the engine achieved a good BSFC characteristic across a wide driving range, and a maximum thermal efficiency of 36.3% (Fig. 24).

As a vehicle, the new NSX achieves a fuel consumption of 21.1 mpg in North American fuel consumption mode and 12.4 km/L in Japanese JC08 mode.

6.3. Emissions Performance

Reducing the volume of exhaust gas when the catalyst

is cold and speeding up the activation of the catalyst are particularly important factors in reducing emissions. In addition, because regulations on soot emissions are becoming more stringent, it is also necessary to reduce the amount of fuel adhesion in the cylinders, which is a factor in the production of soot.

In previous stratified combustion using a wall guide (a cavity), fuel adhesion to the top surfaces of the pistons cannot be prevented. By combining strong tumble motion and double injection by the DI system in the new engine, it has been possible to reduce the amount of fuel adhering to the pistons and to realize weak stratified combustion close to the spark plugs (Fig. 25)⁽²⁾.

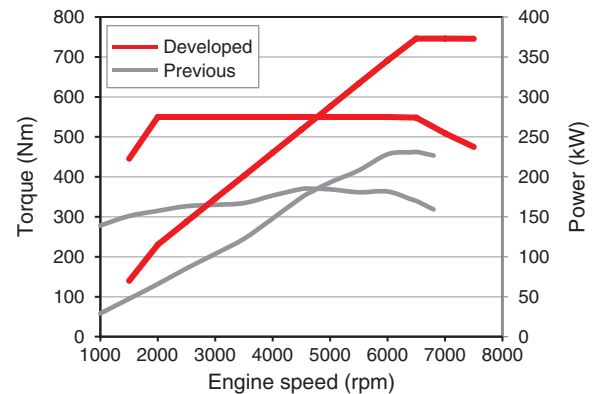


Fig. 23 Engine performance

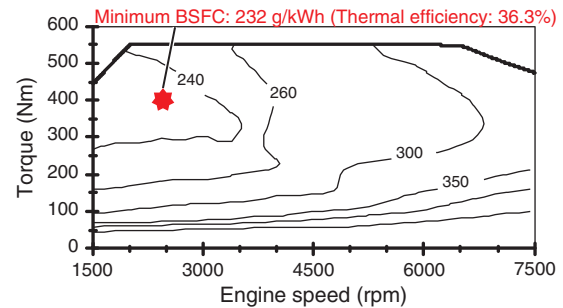


Fig. 24 Engine BSFC map

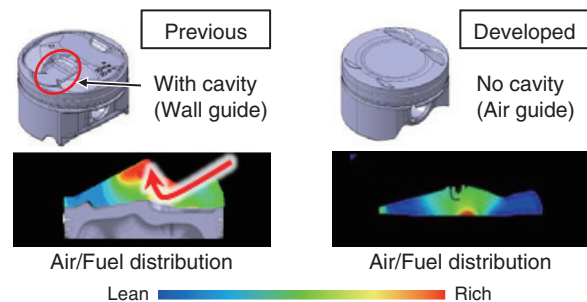


Fig. 25 Stratified combustion concept

Injecting during the intake and compression strokes and optimizing the injection amount and injection timing has achieved an A/F close to the spark plugs that promotes stable combustion, and reduced the amount of fuel adhesion to the pistons to one-half or less that of a conventional engine.

The realization of increased combustion stability has made it possible to retard ignition timing to approximately 20 deg before top dead center. The use of turbochargers has increased heat capacity, which could have reduced the warm-up performance of the catalyst, however the catalyst reaches 300°C or more within 20 sec following engine start (Fig. 26). As a result, mode emissions comply with the European Euro6b and the US ULEV125 regulations.

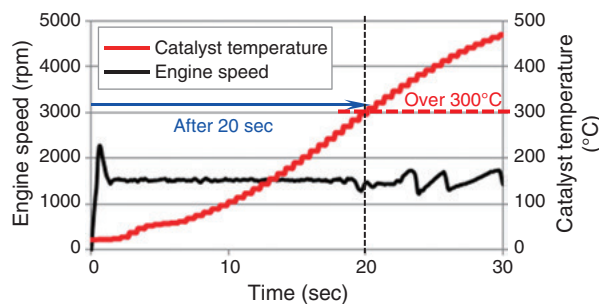


Fig. 26 Catalyst warm-up performance

7. Conclusion

A 3.5 L V6 turbocharged gasoline engine has been developed for the new NSX. As targets, the development of this engine set a high level of power performance and environmental performance, a compact engine layout with a low center of gravity suited to vehicle demands, and a level of engine reliability adequate to sports driving. The development process produced the following results:

- (1) The use of turbochargers and the combustion technologies in-cylinder direct injection and high-tumble ports, and the application of a DI+PI fuel supply system, have made it possible to balance high power characteristics (maximum power of 373 kW (500 HP) and maximum torque of 550 Nm) with emissions performance complying with the European Euro6b and US ULEV125 regulations.
- (2) The use of Fe spray-coated cylinder bores, a dry sump lubrication system, efficiently cooled cylinder heads, a swing arm-type valve train, and reduction chain drive have achieved a lightweight, compact, and low-center-of-gravity engine frame that also achieves a level of reliability, with increased engine power, suited to sports driving.

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