Gasoline Engines

1 Introduction

Global vehicle sales fell heavily due to the global financial crisis that occurred in the wake of the collapse of the Lehman Brothers financial services firm and the U.S. financial crisis in 2008. Since then, despite the ongoing economic uncertainty in Europe, sales have been boosted by the Chinese market (now the largest in the world), a strong recovery in North America, as well as emerging markets in South America and elsewhere. As a result, annual vehicle sales have increased for four consecutive years to a historically high level of 83 million units.

At the same time, fuel economy standards and emissions regulations are becoming increasingly stringent as global awareness of the importance of environmental conservation grows. Developed countries in particular are encouraging a move toward more fuel efficient vehicles through preferential taxation systems. These trends are promoting a generational shift in engine development and a range of new engines have been launched onto the market.

This article introduces the main gasoline engine and new technologies that were developed and launched between January and December 2013. It also summarizes the trends in the research and development of gasoline engines.

2 Japan

2. 1. Summary

The Japanese market has shown signs of recovery from the effects of the global financial crisis in 2008 and the Great East Japan Earthquake in 2011. In particular, the second half of 2013 saw a large increase in sales spurred by last minute demand before the consumption tax hike in April 2014. As a result, sales reached 5.69 million vehicles, the highest for seven years and the highest level since 5.61 million vehicles were sold in 2006. This figure includes sales of mini-vehicles, which increased by 14.7% to a record high of 2.26 million vehicles. The popularity of mini-vehicles continues to increase by virtue of their fuel efficiency and cheapness to maintain. Mini-vehicles now account for 40% of all new vehicle sales.

The competition for even better fuel efficiency is becoming increasingly fierce for those vehicles that are eligible under Japan's preferential tax scheme for environmentally friendly vehicles, which include both mini-vehicles and hybrids. One standout trend in 2013 was the launch of new engines incorporating new technology to increase the compression ratio, such as direct injection and cooled exhaust gas recirculation (EGR).

2. 2. Automaker trends

Table 1 shows a list of the main new types of gasoline engines that were sold by Japanese automakers in 2013. A summary of the new engines developed by each manufacturer is provided below.

2. 2. 1. Toyota

Although the Crown Hybrid has conventionally used a 3.5-liter V6 engine, the inline 4-cylinder 2.5-liter 2AR-FSE engine was developed to further improve fuel efficiency (Fig. 1). Toyota's next generation combustion concept (D-4S) performs both high-pressure (up to 20 MPa) di-

Fig. 1 Toyota 2AR-FSE.

Table 1 Main new gasoline engines in Japan.

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve train	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Special characteristics
Toyota	2AR-FSE	L4	90.0×98.0	2.949	13.0	DOHC 4 V	131/6 000	221/4 200–4 800	Crown Hybrid	Next-generation combustion concept (D-4 S), cooled EGR, Atkinson cycle
Honda	LFA	L4	81.0×96.7	1.993	13.0	DOHC 4 V	105/6 200	165/3 500–6 000	Accord Hybrid	Cooled EGR, electronic VTC, i-VTEC, Atkinson cycle
Nissan	QR25DER	L4 S/C	89.0×100.0	2.488	9.1	DOHC 4 V	172/5 600	330/3 600	Pathfinder	Roots-type supercharger, variable valve timing with mid-position lock, variable fuel pressure system
Mazda	SKYACTIV-G P5 -VPS	L4	74.5×85.8	1.496	13.0	DOHC 4 V	82/6 000	144/3 500	Axela	4-2-1 exhaust manifold, multi-hole injectors, piston cavities
Mitsubishi	3B20	L3	65.4×65.4	0.659	12.0	DOHC 4 V	36/6 500	56/5 500	eK Wagon, Nissan Dayz	Variable valve timing (MIVEC), cooled EGR, electronically controlled thermostat
Suzuki	K12B DJE	L4	73.0×74.2	1.242	12.0	DOHC 4 V	67/6 000	118/4 400	Swift	Dual jet injectors, cooled EGR
Fuji Heavy Industries	FB16	F4 T/C	78.8×82.0	1.599	11.0	DOHC 4 V	125/4 800–5 600	250/1 800–4 800	Levorg	Direct injection turbo (DIT), variable valve timing, dual active valve control system (AVCS), idling stop

Fig. 2 Honda LFA.

rect fuel injection and low-pressure port injection. This concept combines a high compression ratio of 13.0, the Atkinson cycle, and cooled EGR to achieve a thermal efficiency of 38.5%. Mated with a hybrid system, the Crown Hybrid achieves a fuel economy rating of 23.2 km/L in the Japanese JC08 test cycle, equivalent to that achieved by fuel efficient compact vehicles.

2. 2. 2. Honda

In place of the previous 1-motor hybrid system, the new Accord Hybrid uses a new 2-motor system called the i-MMD. At the same time, the innovative new 2.0-liter inline 4-cylinder LFA engine was adopted (Fig. 2). This engine combines the Atkinson cycle with variable valve timing and lift electronic control (VTEC) on the intake side, and cooled EGR to achieve excellent fuel efficiency and a maximum power of 105 kW. For cold starts, the engine uses the small VTEC cam profile. During warm-up, the power generated by the motor is adjusted and used to promote early activation of the catalyst. As a result, the Accord Hybrid for North America satisfies the LEV III-SULEV20 emissions regulations. Furthermore, this engine features an electronic valve timing control (VTC) system that is capable of retarding the valve timing from engine stop, reducing re-start shock.

2. 2. 3. Nissan

In addition to the conventional V6 3.5-liter engine for the North American three-row Pathfinder SUV, Nissan developed and launched the inline 4-cylinder supercharged QR25DER engine (Fig. 3) that combines with a continually variable transmission (CVT)-based 1-motor 2-clutch hybrid system. Integrating this 4-cylinder 2.5-liter engine with a 4-lobe rotor Roots-type supercharger ensures equivalent dynamic performance to the V6 3.5-liter engine, while the downsizing improves fuel economy. Combined with the hybrid system, this engine achieves a fuel economy rating of 26 mpg in the U.S. combined

Fig. 3 Nissan QR25DER.

Fig. 4 Mazda SKYACTIV-G P5-VPS.

mode. This engine also features a VTC system with a mid-position lock mechanism and a port injection variable fuel pressure system, resulting in clean emissions performance that satisfies SULEV regulations by reducing hydrocarbon (HC) emissions on cold starts.

2. 2. 4. Mazda

The SKYACTIV-G concept engine series, which was previously installed on the Demio and Atenza, was extended to the new Axela in the form of the inline 4-cylinder 1.5-liter P5-VPS engine (Fig. 4). The new technologies on this engine are shared with the previously launched 1.3-liter and 2.0-liter engines. Combining a direct injection system that uses multi-hole injectors and piston cavities with cooled EGR and a 4-2-1 exhaust manifold achieves a high compression ratio of 13.0 with regular gasoline and excellent fuel economy of 19.4 km/L in the JC08 test cycle.

2. 2. 5. Mitsubishi

The inline 3-cylinder 0.66-liter 3B20 engine (Fig. 5) is installed on the eK Wagon mini-vehicle and Nissan Dayz, which is supplied by Mitsubishi as an original equipment

Fig. 5 Mitsubishi 3B20.

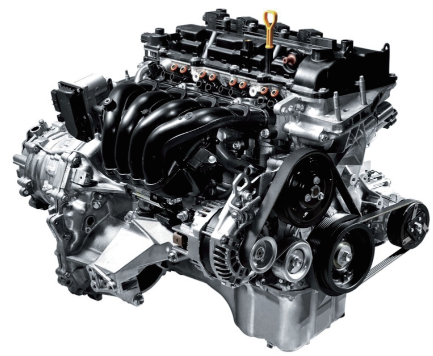

Fig. 6 Suzuki K12B DJE.

manufacturer (OEM). This engine combines the Mitsubishi Innovative Valve Timing Electronic Control (MIVEC) system with an electronically controlled thermostat (a first for a vehicle produced by a Japanese manufacturer), cooled EGR (a first for a mini-vehicle), CVT, and an idling stop system to achieve excellent fuel economy of 29.2 km/L in the JC08 test cycle.

2. 2. 6. Suzuki

A new Swift was launched powered by the inline 4-cylinder 1.2-liter K12B Dual Jet Engine (DJE) (Fig. 6). This engine features two low-pressure port injectors arranged in parallel for each engine (called dual jet injectors) and a cooled EGR system. This achieves a combustion ratio of 12.0 and a fuel economy rating of 26.4 km/L in the JC08 test cycle, the best result for gasoline engine vehicles with a displacement of at least 1.2-liters.

2. 2. 7. Fuji Heavy Industries

Fuji Heavy Industries launched a new touring wagon called the Subaru Levorg as the next generation Legacy, installed with the newly developed horizontally opposed 4-cylinder turbocharged FB16 engine (Fig. 7). Engine downsizing was achieved by adopting intelligent direct injection turbo (DIT) technology, resulting in excellent fuel economy of 17.4 km/L in the JC08 test cycle with a maximum power of 125 kW. In addition, the characteristics of this longitudinally mounted, boxer engine enable symmetrical packaging with a low center of gravity, thereby facilitating the installation of a symmetrical all-wheel drive (AWD) system.

3 U.S.

3. 1. Summary

New vehicle sales in the U.S. in 2013 increased steadily by 7.6% to 15.60 million units due to a strong economy spurred by low interest rates and rising stock prices.

Fig. 7 Fuji Heavy Industries FB16.

This level is close to that achieved before the global financial crisis. All of the Big 3 U.S.-based manufacturers (General Motors (GM), Ford, and Chrysler) and the three major Japanese automakers (Toyota, Honda, and Nissan) also reported higher sales.

As the Corporate Average Fuel Efficiency (CAFE) regulations are strengthened, each of the Big 3 are releasing next-generation engines and adopting innovative technologies to help improve fuel economy. For example, GM has incorporated various technologies into its renowned overhead valve (OHV) V8 engines, such as direct injection, variable valve timing, cylinder deactivation that shuts down one cylinder bank, and an idling stop system. In contrast, Ford has expanded its EcoBoost series of downsized direct-injection turbocharged engines, which achieve equivalent performance to V8 and V6 engines in V6 and inline 4-cylinder formats.

3. 2. Automaker trends

Table 2 shows the main new types of gasoline engines that were sold by U.S. automakers in the U.S. market in 2013. A summary of the new engines is provided below.

3. 2. 1. GM

GM has applied various innovations to develop the

Table 2 Main new gasoline engines in the U.S.

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve train	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Special characteristics
GM	LT1	V8	103.25×92.0	6.162	11.5	OHV 2 V	343/6 000	630/4 600	Chevrolet Corvette	Direct injection, OHV, variable valve timing, single-bank cylinder deactivation mechanism
	L86	V8	103.25×92.0	6.162	11.5	OHV 2 V	313/5 600	624/4 100	Chevrolet Silverado GMC Sierra	Direct injection, OHV, variable valve timing, single-bank cylinder deactivation mechanism
	L83	V8	96.0×92.0	5.328	11.0	OHV 2 V	265 /5 600	519/4 100	Chevrolet Silverado GMC Sierra	Direct injection, OHV, variable valve timing, single-bank cylinder deactivation mechanism
	LV3	V6	99.6×92.0	4.301	11.0	OHV 2 V	213 /5 300	414 /3 900	Chevrolet Silverado GMC Sierra	Direct injection, OHV, variable valve timing
	LF3	V6 2T/C	94×85.6	3.564	10.2	DOHC 4 V	313 /5 750	583 /3 500–4 500	Cadillac CTS	Water-cooled intercooler, direct injection, electronically controlled wastegate
	LKW Ecotec Gen III	L4	88.0×100.8	2.457	11.3	DOHC 4 V	146 /6 300	252 /4 400	Chevrolet Malibu	Intake valve lift control (IVLC), direct injection, idling stop
Ford	EcoBoost	L4	80.0×76.5	1.499	10.0	DOHC 4 V	133 /6 000	240 /1 500–4 500	Fusion	Water-cooled intercooler, direct injection, electronically controlled wastegate
Chrysler	Pentastar	V6	91.0×83.0	3.239	10.7	DOHC 4 V	202 /6 750	324 /4 400	Jeep Cherokee	Variable intake and exhaust valve timing

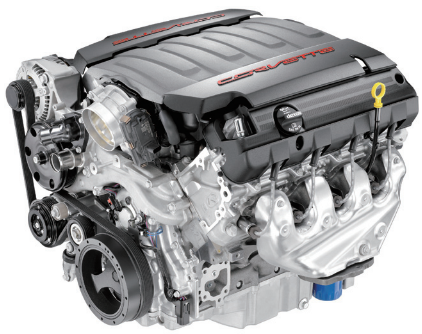

Fig. 8 GM LT1.

Fig. 9 GM L86/L83.

Fig. 10 GM LV3.

Fig. 11 GM LF3.

Fig. 12 GM LKW.

next generation of its so-called small-block 90-degree V8 OHV engine family. For passenger vehicles, the 6.2-liter V8 LT1 engine (Fig. 8) was installed on the Chevrolet Corvette. While maintaining the traditional basic 2-valve design, a direct-injection system has been added, along with variable valve timing that changes the phase of the camshaft provided in the center of the V-shaped cylinder banks, and a cylinder deactivation system that shuts down one cylinder bank using a valve-stop function in the OHV pushrods. As a result, the Corvette achieves a maximum power of 343 kW and excellent fuel economy that avoids the Gas Guzzler Tax.

For trucks, GM adopted the same next-generation 90-degree V8 OHV engine family and a range of derived V6 engines. The 6.2-liter L86 engine (Fig. 9), 5.3-liter L83 engine, and 4.3-liter LV3 engine (Fig. 10) are available on the Chevrolet Silverado and GMC Sierra. Sharing the same basic structure and technologies as the LT1 described above, the Silverado has a rated highway fuel economy of 23 mpg, the highest in the full-size pickup class.

The new CTS launched by Cadillac, GM's luxury brand, uses the V6 3.5-liter twin-turbocharger LF3 engine (Fig. 11). This is a boosted engine with a turbocharger compressor provided on each of the left and right cylinder banks. The engine is cooled by a water-cooled intercooler located at the top of the engine and the boost pressure is precisely controlled by an electronic wastegate. As a result, this engine achieves a maximum power of 74 kW per liter.

The inline 4-cylinder 2.5-liter engine installed in the front-wheel drive (FWD) mid-size Chevrolet Malibu was also updated for the 2014 model year as the Gen III LKW (Fig. 12), which is part of GM's Ecotec engine series. Un-

Fig. 13 Ford 1.5-liter EcoBoost.

Fig. 14 Chrysler 3.2-liter Pentastar.

like the previous LCV engine, the Gen III LKW includes the intake valve lift control (IVLC) system, which is capable of switching between two valve lift settings (4.0 mm and 10.5 mm). Combined with a 6-speed automatic transmission (AT) and an idling stop function, this engine achieves excellent fuel economy of 25 mpg in the city and 36 mpg on the highway.

3. 2. 2. Ford

In recent years, Ford's engine lineup has clearly begun to emphasize downsized turbocharged engines. This trend was further promoted in 2013. The inline 4-cylinder 1.5-liter EcoBoost engine (Fig. 13) installed in the Fusion and Mondeo is positioned to play a strategic role in achieving the global roll out of EcoBoost engines, including to emerging markets. By the end of 2013, Ford had established six production bases in Asia, Europe, and North America with an annual capacity of 1.6 million engines.

3. 2. 3. Chrysler

Chrysler launched the latest generation of its V6 Pentastar engine for the 2011 model year. Since then, it has worked to expand the adoption of this engine and, in 2013, launched a scaled down 3.2-liter version (Fig. 14) compared to the original displacement of 3.6 liters. This engine was installed in the Jeep Cherokee.

4 Europe

4. 1. Summary

In 2013, vehicle sales in Europe fell for the sixth consecutive year. Although there was an improvement in the period from October to December, sparking hopes for a wider recovery, it was not enough to translate into a full year-on-year increase.

Despite the continuing difficult economic situation in the European market, technological competition to improve fuel economy is becoming ever fiercer due to growing environmental awareness, as well regulations and preferential tax schemes in each country aiming to reduce CO_2 emissions. 2013 saw the release of another wave of downsized direct injection turbocharged engines. In fact, all seven of the new engines described below fall into this category.

4. 2. Automaker trends

Table 3 shows the main new types of gasoline engines that were sold by European automakers in Europe in 2013. A summary of the new engines is provided below.

4. 2. 1. Audi

The 1.8-liter and 2.0-liter inline 4-cylinder direct injection turbocharged EA888 engine developed by Audi and Volkswagen (VW) was at the forefront of the downsizing and turbocharging trend. This engine is currently on its third generation and the Power Class 3 (Fig. 15) version installed in the S3 has been designed specifically for high power. It features a dual high- and low-pressure fuel injection system, a variable cooling system using rotary slide valves, and the Audi Valvelift System (AVS), which varies the lift of the exhaust valves. These technologies are common between the standard and high-power engines. However, the Power Class 3 also features a low compression ratio of 9.3 and a high-volume turbocharger, as well as new high-temperature resistant materials adopted for the cylinder head and exhaust valves. These measures help to achieve a maximum power of 206 kW.

4. 2. 2. BMW

The plug-in hybrid i8 uses the inline 3-cylinder 1.5-liter TwinPower Turbo engine (Fig. 16), which combines a turbocharger with direct injection using piezo injectors, the Valvetronic variable valve lift system, and the double VANOS variable valve timing system. The design of this engine is exactly half that of an inline 6-cylinder

Table 3 Main new gasoline engines in Europe.

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve train	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Special characteristics
Audi	EA888 2.0 L TFSI Power Class3	L4 T/C	92.8×82.5	1.984	9.3	DOHC 4 V	206/5 200–6 500	380/1 800–5 200	S3	Cylinder head-integrated exhaust manifold, rotary slide variable valve cooling, dual high- and low-pressure fuel injection, Audi Valvelift System (AVS)
BMW	Twin Power Turbo B38	L3 T/C	82.0×94.6	1.499	11.0	DOHC 4 V	170/5 800	320/3 700	i8	Direct injection, Valvetronic, double VANOS
Daimler	M133 AMG	L4 T/C	83.0×92.0	1.991	8.6	DOHC 4 V	265 /6 000	450/2 250–5 000	Mercedes Benz A45 AMG	Direct injection with piezo injectors, variable intake and exhaust valve timing, 2-stage variable oil pump, twin-scroll turbocharger, water-cooled intercooler
	M276 DELA 30	V6 2T/C	88.0× 82.1	2.996	10.7	DOHC 4 V	245 /5 250–6 000	480 /1 600–4 000	Mercedes Benz E400	Direct injection with piezo injectors, variable intake and exhaust valve timing, 2-stage variable oil pump, water-cooled intercooler
Opel	1.0L SIDI Turbo	L3 T/C	74.0×77.4	0.998	10.5	DOHC 4 V	85 /5 200	166 /1 800–4 700	Adam	Direct injection with piezo injectors, powder metal forged connecting rods, switchable water pump, cylinder head-integrated exhaust manifold, balance shaft-integrated twin-displacement oil pump
Porsche	3.0 L V6 twin turbo	V6 2T/C	96.0×69.0	2.997	9.8	DOHC 4 V	313 /6 000	520 /1 750–5 000	Panamera	Direct injection twin-turbocharger
Volvo	T6 Drive-E	L4 T/C & S/C	82.0×93.2	1.968	10.3	DOHC 4 V	225 /5 700	400 /2 100	S60 XC60 V60	Roots-type supercharger and turbocharger

Fig. 15 Audi 2.0-liter EA888 TFSI Power Class 3.

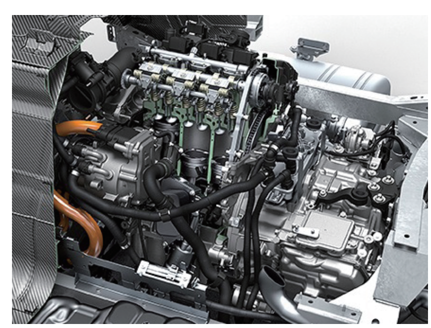

Fig. 16 BMW 1.5-liter Twin Power Turbo.

3.0-liter engine. BMW has announced that it plans to expand the adoption of this engine into a transverse-mounted Mini and a longitudinally mounted 1 Series

4. 2. 3. Daimler

The M133 engine (Fig. 17) was developed by Mercedes-AMG as a high-performance variant of the inline 4-cylinder 2.0-liter turbocharged BlueDirect M270 engine. Although the basic dimensions and structure are carried over from the M270, it features various technologies to cope with the higher combustion pressure, which was raised to 150 bar to boost power. These include the combination of a cylinder liner technology called a Nanoslide coating, which uses a wire explosion plating method, with a closed deck sand-cast low-pressure cylinder block. The cylinder head, exhaust valves, and other parts use high-temperature resistant materials. Although the compression ratio was lowered to 8.6 to increase power, the intake capacity was reduced and a twin-scroll turbo-

Fig. 17 Daimler M133 AMG.

Fig. 18 Daimler M276 DELA30.

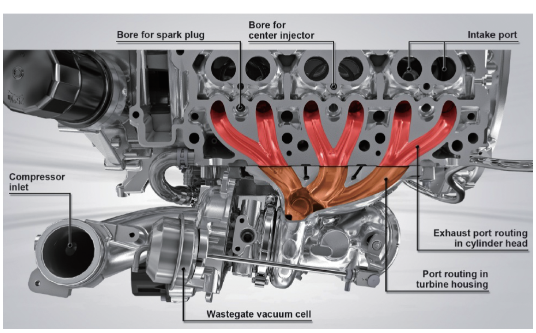

Fig. 19 Cross-section of M276 DELA30 cylinder head and turbocharger.

charger was adopted in consideration of transient torque response. As a result of these technologies, this engine has low CO_2 emissions of 161 g and a high specific power of 133 kW/L, enabling compliance with the North American ULEV125 and Euro 6 emissions regulations.

The Mercedes Benz E400 is installed with the V6 3.0-liter twin-turbocharger M276 DELA30 engine (Fig. 18), which is based on the naturally aspirated (NA) V6 3.5-li-

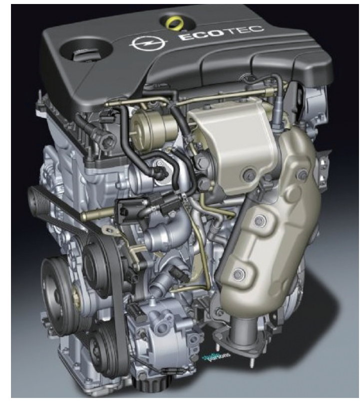

Fig. 20 Opel 1.0-liter SIDI Turbo.

Fig. 21 Direct injection piezo injectors in Opel 1.0-liter SIDI turbocharged engine.

ter BlueDirect M276 DE35 engine. The bore and stroke were both reduced to cut the displacement to 3.0-liters and this engine also uses the Nanoslide coating technology described above to reduce mechanical friction. As shown in the cross-sectional view in Fig. 19, the exhaust passage from the cylinder head to the turbocharger was drastically shortened to reduce capacity and ensure response. This measure also helps to transfer exhaust energy efficiently into turbine work. As a result, the maximum turbine temperature reaches 1,050℃. This engine also uses the same piezo injector direct injection system as the BlueDirect series. As a result, the E400 achieves low fuel consumption of 7.5 liters/100 km and a maximum power of 245 kW.

4. 2. 4. Opel

An inline 3-cylinder 1.0-liter turbocharged spark ignition direct injection (SIDI) engine (Fig. 20) was installed in the new Adam. Direct injection using piezo injectors (Fig. 21) achieves a maximum fuel injection pressure of 20 MPa. The engine integrates the cylinder head with the exhaust manifold to ensure transient response and high-temperature reliability in a compact package. Fric-

Fig. 22 Porsche 3.0-liter V6 twin-turbocharger engine.

tion reduction technologies such as switchable water pump and balance shaft-integrated twin-displacement oil pump also help to achieve power of 85 kW and excellent fuel economy of 369 g/kWh at 2,000 rpme × 2 bar.

4. 2. 5. Porsche

The engine variations for the Panamera were supplemented with a 3.0-liter V6 twin-turbocharger engine (Fig. 22), which replaced the conventional 4.8-liter V8 NA engine. This engine achieves class leading power for a 6-cylinder 3.0-liter twin-turbocharger engine (313 kW).

4. 2. 6. Volvo

Volvo launched the Drive-E series of inline 4-cylinder 2.0-liter direct injection turbocharged engines. There are two engine types in the series: the T5 version, which is equipped with a turbocharger only, and the T6 version (Fig. 23), which includes both a turbocharger and a supercharger. The latter version achieves a maximum power of 225 kW. These engines will be adopted in sequence on Volvo's car lineup, starting with the S60.

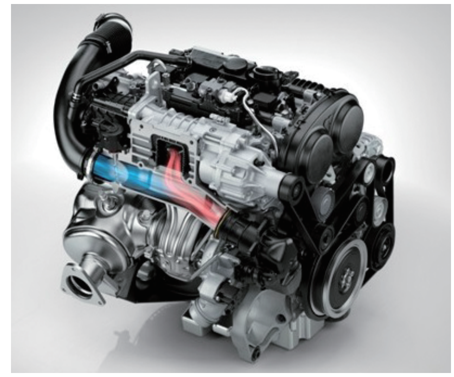

Fig. 23 Volvo Drive-E T6 version.

5 Trends in Research and Development

5. 1. Turbocharging technology

As described above, direct injection downsized turbocharging technology is spreading throughout the world and has become a mainstream option in Japan, the U.S., and Europe. Research is under way from a variety of approaches to help resolve some of the issues associated with further advances in turbocharging technology, such as heavy downsizing and turbo lag. These include driving the turbocharger compressor directly using an electric motor, and two-stage turbocharging using twin-turbochargers arranged in line one after the other.

5. 2. Mixture ignition and combustion technology

As progress is made to increase the compression ratio through the adoption of downsized direct injection turbocharged engines and the Atkinson cycle, growing demands are being placed on technological fields related to appropriate mixture ignition and stable combustion. Aside from the conventional fields of achieving more intense and precise ignition energy, and carrying out multiple or multi-point ignition, much research is being reported about exotic technologies such as laser, corona, and microwave plasma ignition. Although there are many issues to be resolved before practical adoption, research in these fields is likely to become more active in the future.

5. 3. Homogeneous charge combustion ignition (HCCI) technology

Although research into HCCI is continuing, many issues remain to be resolved, such as limited usage regions, and the difficulty of control to ensure stable self-ignition and combustion. Much research in 2013 focused on mechanism analysis and modeling.