GASOLINE ENGINES

1 Introduction

Regulations on fuel economy (CO_2) and emissions have been becoming tighter in various countries in recent years. Making further improvements in automotive engines is necessary. Under these circumstances, automakers are aggressively releasing technologies to achieve highly efficient, and low emission engines. They have also released a succession of technologies to improve the thermal efficiency of engines for hybrid vehicles.

An overview of the regulations is presented below. Fuel economy regulations in the Europe are the strictest around the world. Moreover, CO_2 regulations will become more stringent from 2020. Emissions were conventionally measured only in a specified mode. However, real driving emission (RDE) regulations were implemented in 2017 to reduce the environmental burden imposed by actual driving in the real world. The scope of the regulations has thus been extended to emissions emitted when vehicles drive on actual roads. In the U.S., the zero emission vehicle (ZEV) regulations, which are enforced in California and other states, have become stricter since 2018. Consequently, the demand for the introduction of electric vehicles, including BEVs and plug-in hybrid vehicles, has been intensifying.

This article introduces the new technologies used in the main gasoline engines launched or announced in 2018, and presents the research and development trends for such engines.

2 Japan

2. 1. Overview

Sales of new vehicles in Japan in 2018 reached 5.27 million vehicles, an increase of 0.7% compared to 2017, for registered and mini-vehicles combined. Mini-vehicles accounted for 36.5% of all new vehicle sales[2].

Efforts to improve the thermal efficiency of gasoline engines are underway. Thermal efficiency of gasoline engines has been improved on a continuous basis. Previously, it was considered that technologies such as variable compression and compression ignition were difficult to put into practical use. However, engines using these technologies were unveiled.

2. 2. Trends of Each Manufacturer

Table 1 lists the new engines launched or announced by manufacturers in Japan in 2018, which are summarized below.

2. 2. 1. Toyota

Toyota announced the Toyota New Global Architecture (TNGA) in 2016, and developed new engine families which were modularized by commonizing combustion characteristics.

The release of a 2.5-liter naturally aspirated engine in 2017 was followed by the M20A-FKS and M20A-FXS 2.0-liter naturally aspirated engines (Fig. 1). These engines commonize the bore/stroke and the compression ratio, as well as the angle between the intake and exhaust valves, of the 2.5-liter engine. By controlling the bore diameter and turbulent energy as indices, the 2.0-liter engines have the same combustion characteristics as the 2.5-liter engine. In addition, the 2.0 liter engines commonize thermal efficiency improvement technologies, such as the laser clad valve seat with the 2.5 liter engine. The 2.0-liter engines are also the first in the world to use a piston with a laser pit skirt to reduce mechanical resistance. Their highest thermal efficiency and output performance reach 40% and 62.5 kW/L for conventional vehicles, and 41% and 50 kW/L for hybrid vehicles. These engines are installed in the Lexus UX, and the Auris for the European market[1][3].

2. 2. 2. Nissan

The engine with the variable compression ratio, which was mass-produced first in the world, the KR20DDET VC-Turbo (Fig. 2), was installed in the Infiniti QX50. Generally, it is difficult to achieve both high compression ratio and high output. A higher compression ratio improv-

Table 1 Main New Engines in Japan

Manufacturer	Engine type*1	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve system VVT valve train*2 specifications In/Exh	Intake system	Fuel injection system*3	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Characteristics
Toyota	M20 A-FKS	L4	80.5 × 97.6	1.986	13.0	DOHC 4-valve Roller rocker Electric/hydraulic	NA	S-DI (20 MPa) +PFI	128/6,600	209/4,000–5,200	UX200	High tumble port, intake laser-clad valve seat, laser pit skirt piston, 20 MPa direct injection (DI) system and port fuel injection (PFI), electric variable capacity oil pump, water jacket spacer, electric water pump (WP), fluid control valve (path switching valve), EGR cooler.
	M20 A-FXS	L4	80.5 × 97.6	1.986	14.0	DOHC 4-valve Roller rocker Electric/hydraulic	NA	S-DI (20 MPa) +PFI	107/6,000	188/4,400	UX250 h (HEV) Europe Auris (HEV)	
Nissan	KR20 D-DET VC-TURBO	L4	84.0 × 88.9 (ε14) –90.1 (ε8)	1.970 (ε14) ~ 1.997 (ε8)	8.0~14.0	DOHC 4-valve Direct tappet Electric/hydraulic	TC	S-DI (20 MPa) +PFI	200/5,600	390/1,600–4,800	Infinity QX50	Variable compression ratio (multi-link mechanism), high tumble port TCV, DI and PFI, exhaust manifold integrated in head, mirror bore coating (aluminum alloy), two-stage variable capacity oil pump, fluid control valve (coolant stoppage during warm-up), electric waste gate valve (WGV).
Honda	Accord HEV for L4 2.0 L	L4	81 × 96.7	1.993	13.5	DOHC 4-valve Roller rocker Hydraulic/—	NA	PFI	107/6,200	175/3,500	Accord (HEV)	Mirror-smooth valve, sodium (Na)-filled valve, EGR cooler, exhaust heat recovery equipment, electric WP.
Subaru	FA24	H4	94 × 86	2.387	10.6	DOHC 4-valve Roller rocker Hydraulic/hydraulic	TC	S-DI	194/5,600	376/2,000–4,800	North American Ascent	High tumble port, electric WGV
	FB25	H4	94 × 90	2.498	12.0	DOHC 4-valve Roller rocker Hydraulic/hydraulic	NA	S-DI	136/5,800	239/4,400	Forester	High tumble port, tumble control valve (TCV), fluid control valve.
Suzuki	K15 B	L4	74 × 84.9	1.460	10.0	DOHC 4-valve Direct tappet Hydraulic/—	NA	PFI	75/6,000	130/4,000	Jimny Sierra	Long nozzle injector
Mitsubishi	4 B40	L4	75 × 84.8	1.498	10.0	DOHC 4-valve Direct tappet Hydraulic/hydraulic	TC	S-DI (20 MPa) +PFI	110/5,500	240/2,000–3,500	Eclipse Cross	Exhaust manifold integrated in head, exhaust encapsulated sodium valve, inclined flow turbine, electric WGV.
Mazda	SKYACTIV-X (European specification)(not yet released)	L4	83.5 × 91.2	1.997	16.0	DOHC 4-valve Roller rocker Electric/electric	Highly responsive air assist	C-DI	140	230	Mazda3	Spark controlled compression ignition (SPCCI), lean-burn, highly responsive air assist, EGR cooler, cylinder pressure sensor (CPS).

*1 : Engines announced between January and December 2018 but not yet on sale are indicated as "not released".
*2 : In this article, VVT is used as a unified designation for camshaft position variable mechanisms.
*3 : S-DI and C-DI represent, respectively, side and center layout direct injection, and the figure in parentheses indicates the direct injection maximum fuel pressure.

Fig. 1 Toyota M20A-FKS

Fig. 2 Nissan KR20DDET

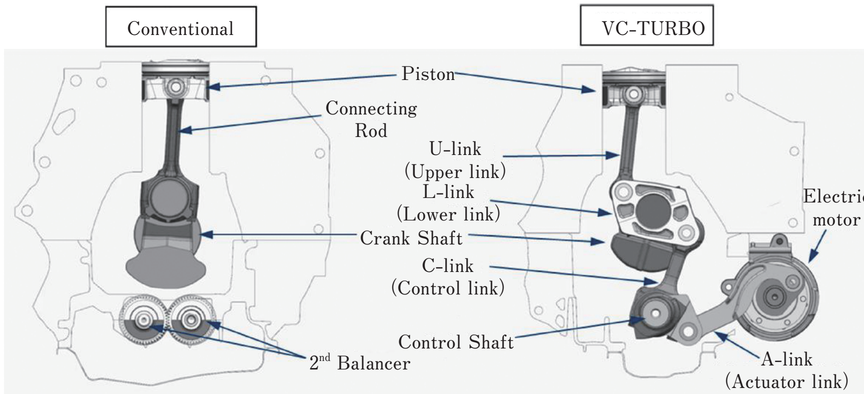

Fig. 3 Nissan multi-link variable compression ratio mechanism

Fig. 4 Honda Accord HEV 2.0-liter L4 engine

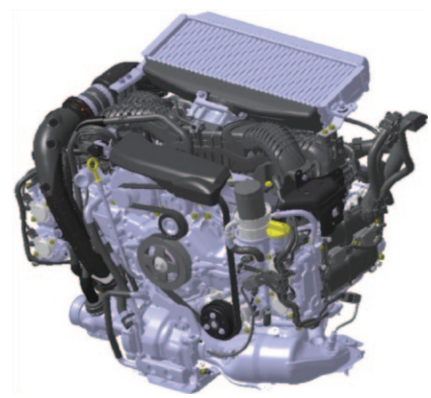

Fig. 5 Subaru FA24

Fig. 6 Subaru FB25

ing its fuel efficiency. However, raising the compression ratio tends to cause engine knock and excessively high cylinder pressure. The engine uses a multi-link variable compression ratio mechanism (Fig. 3) to variably change the compression ratios from 8:1 to 14:1 according to the load and has achieved both better thermal efficiency and high output. Other adopted technologies include a variable valve timing (VVT) mechanism for the intake and exhaust systems, both port fuel injection (PFI) and direct injection (DI) for the injection system, and a turbocharger with a waste gate valve. The exhaust manifold is integrated into the cylinder head. To reduce mechanical resistance and related factors, the engine uses a fluid control valve to achieve a swift warm-up, mirror bore coating, and an offset crank mechanism[(1)(4)].

2. 2. 3. Honda

Honda unveiled a new model 2.0-liter engine that achieves a thermal efficiency of 40% or higher (Fig. 4) and was installed in the new Accord. The engine was designed to achieve better thermal efficiency in hybrid vehicles. The compression ratio is raised to 13.5 from the previous 13.0. In addition, both pumping loss and knocking are reduced by introducing a large amount of recirculated exhaust gas (exhaust gas recirculation: EGR). Other anti-knocking measures include adopting mirror-smooth intake valves and sodium (Na)-filled exhaust valves. To reduce mechanical resistance, the opening temperature of thermostat valve is increased in order to raise the temperature of lubricant. Consequently, viscosity of lubricant is decreased[(1)].

Fig. 7 Suzuki K15B

Fig. 8 Mitsubishi 4B40

Fig. 9 Mazda SKYACTIV-X

2. 2. 4. Subaru

Subaru released the FA24 2.4-liter H4 turbocharged engine (Fig. 5) and the FB25 2.5-liter H4 naturally aspirated engine (Fig. 6).

The FA24 was installed in the Ascent. This engine was derived from FA20 DIT 2.0-liter turbocharged engine, and feature an increased displacement resulting from a larger bore diameter. Port and piston shapes were designed to obtain a high tumble compensate for the reduction in fluid energy due to the increased bore diameter. To reduce knocking tendency, the cylinder head is shaped to make the coolant actively flow toward the intake valve seat. Adopting an electric WGV decreased exhaust pressure, which leads to reduction in both pumping loss and knocking.

The FB25 was installed in the new Forester. Actively adopting EGR both reduces pumping loss and alleviates knocking, improving thermal efficiency. To ensure ignitability while introducing EGR, various technologies are used to enhance the flow in the cylinders. The ports are shaped to strengthen tumble, and tumble generator valves (TGVs) are used. The shape of the combustion chamber was optimized to maintain a strong flow through the use of crown-shaped piston heads and the adoption of an air guide system. Water flow is actively controlled for thermal management. Fluid control valves are used in order to switch coolant paths quickly. This makes it possible to increase low coolant temperature quickly and reduce coolant temperature when a high load is imposed. As a result, both fuel economy and output are improved[(1), (5)-(7)].

2. 2. 5. Suzuki

The K15B 1.5-liter L4 engine (Fig. 7), which is installed in the new model Jimny Sierra, has a shorter bore pitch and lighter weight than conventional engines. The auxiliary belt is covered to address in consideration of off-road operational conditions or other severe conditions. Long nozzle injectors were adopted to inject fuel from a position closer to the combustion chamber than in conventional PFI[(1)].

2. 2. 6. Mitsubishi

The newly developed 4B40 1.5-liter L4 turbocharged engine (Fig. 8), installed in the Eclipse Cross, was launched in March. The injection system relies on both PFI and DI to improve combustion. A VVT mechanism is introduced into in the intake and exhaust systems. The exhaust manifold is integrated into the cylinder head. A WGV is used for the turbocharger[(1)].

2. 2. 7. Mazda

The SKYACTIV-X (Fig. 9), compression ignition engine by utilizing a spark plug as a control factor and method to control compression ignition, is installed in the new Mazda3. The SKYACTIV-X realized a “variable compression ratio”, in which a fireball created by a spark plug expands and further compresses the mixture inside the combustion chamber, quickly reaching optimum cylinder temperature and pressure for compression ignition.

Mazda named this combustion method "Spark Controlled Compression Ignition (SPCCI)" combustion.

Key parameters for thermal efficiency improvement are a compression ratio and specific heat ratio. A specific heat ratio can be improved by lean burn which burns fuel with a large amount of air in a combustion chamber. In a spark ignition engine, however, it is difficult to realize stable combustion with lean mixture in an excess air ratio of two or higher that has less NOx emissions and leads to good thermal efficiency. To solve these problems, finely controlled injection and flow control in the cylinder are used to form the desired mixture, and perform the SPCCI. This achieves stable lean-burn combustion. The hardware adopted to achieve this includes high pressure injectors, a highly responsive air supply mechanism, and cylinder pressure sensors (CPSs)[1].

3 North America

3. 1. Overview

Sales of new vehicles in North America in 2018 reached 17.17 million vehicles, an increase of 0.3% compared to 2017. As corporate average fuel economy (CAFE) standards have become more stringent, automakers are using approaches such as expanding the use of start-stop systems to raise fuel efficiency. North American automakers have expanded the use of exhaust manifold integrated into the cylinder head in their downsized engines to counter knocking and enhance fuel economy.

3. 2. Trends of Each Manufacturer

Table 2 shows the major new engines launched in the North American market in 2018, which are summarized below.

3. 2. 1. Ford

The 1.0-liter L3 and the 1.5-liter L3 turbocharged EcoBoost engines were installed in the new Focus launched in 2018. Both engines perform cylinder deactivation, a world first technology in 3-cylinder engines. The cylinder deactivation system is configured to use a hydraulic lash adjuster (HLA) to stop valve operation. These engines use exhaust manifold integrated into the cylinder head. The other technologies used differ between the engines. The 1.0-liter engine uses a 25 MPa DI system and a gasoline particulate filter (GPF). In contrast, the 1.5-liter engine adds PFI injectors for a combined PFI and DI system intended to obtain better fuel economy and reduce particulate emissions under light load conditions. The engine has a larger bore stroke ratio than the 1.0-liter engine, and uses an offset crankshaft to reduce resistance[9].

3. 2. 2. GM

Newly developed 4.2-liter V8 (Fig. 10) and 2.0-liter L4 (Fig. 11) turbocharged engines were introduced.

The 4.2-liter V8 turbocharged engine was installed in

Table 2 Main New Engines in North America

Manufacturer	Engine type*1	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio	Valve system VVT valve train*2 specifications In/Exh	Intake system	Fuel injection system*3	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main installation vehicles	Characteristics
Ford	1.0 L L3 TC EcoBoost	L3	71.9 × 82.0	0.999	10.5	DOHC 4-valve Cylinder deactivation Electric/electric	TC	C-DI (25 MPa)	63/4,000–6,000 74/4,500–6,000 92/6,000	170/1,400–3,500 170/1,400–4,000 170/1,400–4,500	Focus	Cylinder deactivation, gasoline particulate filter (GPF)
	1.5 L L3 TC EcoBoost	L3	84.0 × 90.0	1.497	11.0	DOHC 4-valve Cylinder deactivation Hydraulic/hydraulic	TC	DI+PFI	110/6,000 134/6,000	240/1,600	Focus, Fiesta ST, Eco-sports	Cylinder deactivation, DI and PFI, GPF
GM	4.2 L V8 TC LTA	V8	86.0 × 90.2	4.192	9.8	DOHC 4-valve Roller rocker Electric/electric	TC	DI (35 MPa)	410/5,600	650/1,800	CT6-V	Intake manifold integrated intercooler, exhaust manifold integrated head, 35 MPa DI system
	2.0 L L4 TC Ecotec	L4	83.0 × 92.3	1.996	Undisclosed	DOHC 4-valve Cylinder deactivation Electric/electric	TC	DI (35 MPa)	177/5,000	350/1,500–4,000	XT4 CT6	35 MPa DI system, TriPower System

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*3 : S-DI and C-DI represent, respectively, side and center layout direct injection, and the figure in parentheses indicates the direct injection maximum fuel pressure.

Fig. 10 GM 4.2-Liter V8 Turbocharged Engine

Fig. 11 GM 2.0-Liter L 4 Turbocharged Engine

the Cadillac CT6-V. The cylinder block make a stable structure capable of handling the 2.54 MPa BMEP and a stepped drill was used to flow coolant between the cylinders. A cylinder head with an integrated exhaust manifold and features two twin-scroll turbochargers, mounted to each bank in the valley. A 35 MPa direct injection fuel system was selected to minimize particulate emissions and enable fast combustion.

The 2.0-liter L4 turbocharged engine was installed in the Cadillac XT4 and CT6. It is the 8th generation in the GM Ecotec engine family. The valve train uses the tripower system, which consists of a switchable cam mechanism that allows the switching of cams in three stages. Specifically, the engine switches to 4-cylinder operation with a large valve lift, a fuel economy-oriented 4-cylinder operation with a small valve lift, or a 2-cylinder operation, depending on the engine speed and load. The injection system adopts a DI system with an injection pressure of 35 MPa to obtain a high torque output at low engine speeds.

4 Europe

4. 1. Overview

New vehicles sales in Europe (within EU nations) in 2018 reached 15.6 million vehicles, the largest figure since 2007.

In Europe, certification of CO_2 emissions in line with the Worldwide harmonized Light vehicles Test Procedure (WLTP) has been mandatory for new models since September 2017. The WLTP has been extended to existing vehicles since September 2018, making WLTP certification mandatory for all vehicle models.

The tightening of particulate emissions and RDE regulations has led to the broad adoption of high pressure DI systems with a level of 35 MPa or injection systems including both PFI and DI, as well as GPFs, to improve combustion.

4. 2. Trends of Each Manufacturer

Table 3 shows the major new engines launched in the European market in 2018, which are summarized below.

4. 2. 1. BMW

New 3.0-liter L6 and 2.0-liter L4 turbocharged engines were introduced into the Z4 scheduled for release in the spring of 2019. BMW's 3-, 4-, and 6-cylinder engines conventionally have a modular configuration with standardized basic structures, such as bore and stroke dimensions, for a single cylinder. The newly developed engines have more standardized components to improve cost and production efficiency, and to deploy fuel economy technologies to a wider range of models. The adopted technologies are described here. For the first time with a 6-cylinder engine, a cylinder head integrated exhaust manifold, in connection with a flanged Twinscroll turbocharger. The valve train system, Valvetronic and Double VANOS, allows variable cumshaft timing and optimal valve lifting. A 35 MPa direct injection fuel system was selected to minimize particulate emissions and improve combustion. The cooling system uses electric fluid control valves to circulate coolant to the cylinder block and the cylinder heads separately. This shortens the cylinder wall warm-up time, providing an early reduction of the piston sliding resistance after the engine starts. Trumpet honing, which widens the cylinder bore toward the bottom like a trumpet, was applied to the cylinder walls to reduce resistance. The 6-cylinder engine also has GPFs as standard equipment to lower emissions. The new 4-cylinder engine also incorporates the same technologies

Table 3 Main New Engines in Europe in 2017

Manu-facturer	Engine type*1	Cylinder arrange-ment	Bore × stroke (mm)	Displace-ment (L)	Compres-sion ratio	Valve system VVT valve train*2 specifi-cations In/Exh	Intake system	Fuel injection system*3	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main in-stallation vehicles	Characteristics
BMW	L4 2.0-liter TC for Z4 (Not released)	L4	82.0 × 94.6	1.998	10.2	DOHC 4-valve Hydraulic/hydraulic	TC	C-DI (35 MPa)	145/4,500–6,500	320/1,450–4,200	Z4 (Not released)	Exhaust manifold integrated head, two system cooling system, 35 MPa DI system and PFI, twin scroll turbochargers, trumpet honing bore, GPF.
	For Z4 .Z5 L6 3.0-liter TC	L6	82.0 × 94.6	2.998	11.0	DOHC 4-valve Hydraulic/hydraulic	TC	C-DI (35 MPa)	250	450–500	Z4 (Not released), X5	
FCA	FireFly 1.0 L L3 TC	L3	70.0 × 86.5	0.999	10.5	DOHC 4-valve MultiAir/HLA	TC	DI (20 MPa)	88/5,750	190/1,750	500 X	MultiAir, intake manifold integrated intercooler, exhaust manifold integrated head, 20 MPa DI system, thermal spray bore (aluminum alloy), GPF.
	FireFly 1.3 L L4 TC	L4	70.0 × 86.5	1.332	10.5	DOHC 4-valve MultiAir/HLA	TC	DI (20 MPa)	110/5,250	270/1,850	500 X	
	2.0 L L4 TC Hurri-cane	L4	84.0 × 90.0	1.995	10.0	DOHC 4-valve Roller rocker Electric/electric	TC	DI (29 MPa)	200/5,250	400/3,000	Jeep Wrangler	Exhaust manifold integrated head, twin scroll turbochargers, EGR cooler, 20 MPa DI system, electric WGV.
Renault	HR10 DDT (Not released)	L3	72.2 × 81.3	0.998	11.0	DOHC 4-valve Roller rocker Hydraulic/hydraulic	TC	C-DI (25 MPa)	86/5,250	180/1,750–4,000	Not for sale	Delta cylinder head, bore spray coating, 25 MPa DI system, electric WGV.
	1.8 L L4 TC M5P	L4	79.7 × 90.1	1.798	Undis-closed	DOHC 4-valve Direct tappet Hydraulic/hydraulic	TC	DI	205/6,000	390/2,400–4,800	Mégane R.S. Alpine A110	Mirror bore coating, DI system, twin scroll turbochargers.

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*3 : S-DI and C-DI represent, respectively, side and center layout direct injection, and the figure in parentheses indicates the direct injection maximum fuel pressure.

Fig. 12 FCA FireFly 1.0-Liter L3 Turbocharged Engine

Fig. 13 FCA FireFly 1.3-Liter L4 Turbocharged Engine

as the 6-cylinder engine(10)(11).

4. 2. 2. FCA

Newly developed FireFly 1.0-liter L3 (Fig. 12) and 1.3-liter L4 (Fig. 13) turbocharged engines were mounted on the Fiat 500X at the end of July. These two engines are variations that have a modular configuration with a displacement of 0.33 L per cylinder, and a different number of cylinders. The conventional FCA unique hydraulic valve train system, called MultiAir, has function to continuously vary valve timing and valve lift amounts. The new 1.0-liter and 1.3-liter engines use an advanced version of the MultiAir system that has function to control vale opening and closing timing independently besides the conventional function. Knocking under high load conditions is reduced by effectively feeding internal EGR to the combustion chamber. Due to a combination of the MultiAir system, long stroke design, and a DI system with a 20 MPa injection pressure, the Atkinson cycle is achieved, which increases thermal efficiency. The engines also have GPFs as standard equipment to lower

Fig. 14 FCA 2.0-Liter L4 Turbocharged Engine

emissions.

The Jeep Wrangler is equipped with the new 2.0-liter L4 turbocharged engine (Fig. 14), which can be combined with mild hybrid vehicles. The engine has exhaust manifold integrated into the cylinder head and twin scroll turbochargers. Combining the EGR cooler and the DI system with a 29 MPa injection pressure improves fuel efficiency. Independent cooling circuits are set in the throttle and turbochargers[12].

4. 2. 3. Renault

Renault released 1.0-liter L3 and 1.8-liter L4 turbocharged engines.

The HR10DDT 1.0-liter L3 turbocharged engine was derived from the HR13DDT 1.3-liter L4 turbocharged engine that was released in 2017. As with the HR13DDT, it was jointly developed by Renault, Daimler, and Nissan. The 3-and 4-cylinder engines have a modular configuration that shares a bore diameter of 85 mm and single cylinder capacity of 0.33 L. Similarly, the use of bore spray coating technology and very compact and the delta cylinder head is common to both engines. Their intake system is a modular 4-cylinder design that is applicable to similar models with minimal modification. A 25 MPa direct injection fuel system and GPFs are adopted to lower emissions[12].

The new 1.8-liter L4 turbocharged engine was installed in the Mégane R.S. that was launched in 2018. Engineers who developed Renault's sports and racing cars were involved in the development of this new engine. It has an output of 205 kW, and is equipped with a DI system and twin scroll turbochargers. It also incorporates the resistance reduction technologies of diamond like carbon (DLC) coating for the valve lifter, and mirror bore coating for the cylinder walls found in other Renault engines[8].

5 Trends in Research

5. 1. Government-Industry-Academia Collaboration

The Innovative Combustion Technology program, which is part of the Cross-ministerial Strategic Innovation Promotion Program (SIP), announced that it had achieved a net maximum thermal efficiency exceeding 50% for both gasoline and diesel engines in passenger cars. Technologies that improve net thermal efficiency, such as the use of super lean-burn to improve indicated thermal efficiency and the reduction of mechanical loss, were incorporated into gasoline engines.

The activities of this program led to significant progress in phenomena analysis and in modeling. Various zero-, one-, and three-dimensional models for passenger car engines were developed. Such models include injection, ignition, flame propagation, PM generation, wall surface cooling loss, knocking, lubrication, abrasion, and seizing. The three-dimensional models were developed using the HINOCA software. These models are expected to serve as the basis for the model based development promoted by the Research Association of Automotive Internal Combustion Engines (AICE)[1][14].

5. 2. Combustion Technologies

Japanese and European automakers announced technologies to reduce knocking tendency under high load conditions. A technology using water injection to cool the cylinders was put into practical use by BMW and other automakers. Fuel injection technologies that allow a high fuel injection pressure near the compression top dead center and rapid combustion in the divided combustion chamber have also been reported[1].

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