GASOLINE ENGINES

1 Introduction

At the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21) held at the end of 2015, the Paris Agreement was adopted, suddenly making regulations to improve automobile fuel efficiency and achieve clean emissions stricter, particularly in developed countries. In contrast, motorization is making remarkable inroads in emerging countries, with air pollution reaching alarming levels in some urban areas. In China, India, and other countries, regulations as strict as those of developed countries are scheduled to be introduced.

The soon-to-be-introduced Worldwide harmonized Light vehicles Test Procedure (WLTP) made into an international standard mainly through the efforts of Japan, Europe and emerging countries increases the number of high load range cycles closely matching actual driving than current test methods. It is therefore predicted to significantly impact improvement trends and introduced technologies for gasoline engines.

This article introduces the main new gasoline engines and incorporated engine technologies developed and launched between January and December 2016, and also presents an overview of the research and development trends concerning these engines.

2 Japan

2.1. Overview

In 2016, the Japanese marked was affected by the Kumamoto earthquake and fuel economy scandals by a subset of automakers, but sales of new vehicles (total of registered vehicles and mini-vehicles) nevertheless increased by 2.8% to reach 5.08 million vehicles, breaking past the 500 million mark for the first time in two years. Registered vehicles sales for the same period have been positive for two consecutive years, increasing by 7.5% to reach 3.36 million vehicles, while mini-vehicle sales during that period have been negative for three consecutive years, decreasing by 5.1% and falling to 1.72 million vehicles[1]. The proportion of hybrid vehicles is rising, and new and upgraded engine incorporate both natural aspiration and turbocharging. The current state of affairs at the various automakers is presented below.

2.2. Automaker Trends

Table 1 shows a list of the main new types of gasoline engines sold or announced by Japanese automakers in 2016. An overview (including engines sold or announced outside Japan by Japanese manufacturers) is provided in this section.

2.2.1. Toyota

In December, the outline of the new powertrain based on the TNGA concept was unveiled[2]. The growing modularity of engines is planned to reduce the number of types by approximately 40% and lead to the introduction

Fig. 1 Toyota Dynamic Force Engine

Fig. 2 Nissan HR12DE

Table 1 Main new gasoline engines in Japan in 2016.

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (cc)	Compression ratio	Valve train	Intake system	Fuel injection system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles equipped with this motor	Characteristics
Toyota	Undisclosed (Dynamic force engine)	L4	ϕ87.5× 103.4	2 487	13 (HVs: 14)	DOHC 4V Roller rocker	NA	DI+ PFI	(HVs: 130/5 700)	(HVs: 220/3 600–5 200)	North American Camry, others	○Fuel economy (thermal efficiency) / Performance • High-speed combustion technologies Long stroke, expanded valve included angle, high efficiency intake port (laser clad valve seat) High ignition energy, new D4 -S, multi-hole injectors • Variable cooling system Electric water pump, electronically-controlled thermostat • Continuous variable capacity oil pump • Low viscosity oil • Jacket spacer ○High response • VVT-iE • Small-concave-profile camshaft • Compact hydraulic lash adjuster • High-strength connecting rod • High-response intake airflow control ○Low emissions • Fuel injection control (split injection) • Cylinder heads with built-in EGR cooler function • New catalyst • Rear exhaust • Piston oil jet control system
Nissan	HR12DE	L3	ϕ78.0× 83.6	1 198	12	DOHC 4V Direct tappet	NA	PFI (dual)	58/5 400	103/3 600–5 200	Note (e-POWER)	Mirror bore coating, dual injectors Cylinder head with integrated exhaust manifold, EGR cooler Electric water pump
	MR20DD	L4	ϕ84.0× 90.1	1 997	12.5	DOHC 4V Direct tappet	NA	DI	110/6 000	200/4 400	Serena	Mirror bore coating, electric tumble flap control, cylinder head with three exhaust ports, EGR cooler, sodium-filled valve, DLC piston ring, resin-coated piston skirt, dual arm tensioner
	Undisclosed (VC turbocharger)	L4	ϕ84.0× 94.1	1 970～ 1 997	8～14	DOHC 4V Direct tappet	TC	DI+ PFI	200	390	Infiniti	Variable compression ratio
Honda	JNC	V6	ϕ91.0× 89.5	3 492	10	DOHC 4V	TC	DI+ PFI	373/6 500 −7 500	550/2 000–6 000	NSX	Continuous variable valve timing control High-tumble intake port, plasma spray-coated cylinders High capacity, low pressure loss twin intercooler 75° V-bank angle, dry sump oil circulation
Subaru	FB20	H4	ϕ84.0× 90.0	1 995	12.5	DOHC 4V Roller rocker	NA	DI	113/6 000	196/4 000	IMPREZA	Direct injection adopted, flow path of tumble generation valve modified
Daihatsu	1KR-FE	L3	ϕ71.0× 83.9	996	12.5	DOHC 4V Direct tappet	NA	PFI (dual)	51/6 000	92/4 400	Boon, Passo	Dual intake ports and dual injectors High response stepper EGR valve, Atkinson cycle New resin coat adopted on piston skirt surface

Table 1 Main new gasoline engines in Japan in 2016 (cont.)

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (cc)	Compression ratio	Valve train	Intake system	Fuel injection system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles equipped with this motor	Characteristics
Daihatsu	1KR-VET	L3	ϕ71.0× 83.9	996	9.5	DOHC 4V Direct tappet	TC	PFI (dual)	72/6 000	140/2 400–4 000	Thor, Roomy/Tank, Justy	Dual intake ports and dual injectors Cylinder heads with a three-piece water jacket, drilled passages between exhaust valves Positive crankcase ventilation system that uses an ejector

Fig. 3 Nissan MR20DD

Fig. 4 Nissan VC Turbocharger

Fig. 5 Honda JNC

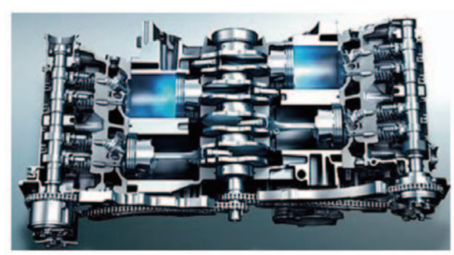

Fig. 6 Subaru FB20

of 19 models with 37 variations by 2021. For gasoline engines, two models of the Dynamic Force 4-cylinder, 2.5-liter engine (Figure 1) were introduced, one for conventional vehicles, and one for hybrid vehicles. This engine adopts the high-speed combustion technologies of a long stroke design with a stroke/bore ratio of approximately 1.2, an expanded valve included angle, and a high efficiency intake port achieved through laser cladding. Also, the adoption of multi-hole direct injectors, continuous variable capacity oil pump, and other parts achieve a maximum thermal efficiency of 41% (in hybrid vehicles, 40% in conventional vehicles) and a specific power of 60 kW/L. Mass production will start with its installation in the North American Camry.

2. 2. 2. Nissan

The new e-Power powertrain in the Note announced in November has drawn attention, and the engine used to raise the matching level of the e-Power is the HR12DE (Figure 2)[2].

Compared to current designs, this engine uses a cylinder block finished with mirror bore coating, a cylinder head with integrated exhaust manifold, and EGR cooler, dual injectors, an electric water pump, and other technologies that raise the compression ratio from 10.2 to 12.0 and, in combination with high output motors, achieves a fuel economy of 37.2 km/h in the JC08 test cycle.

The MR20DD engine mounted in the Serena unveiled in August (Figure 3)[2] distinguishes itself from past engines by adopting technologies such as a cylinder block

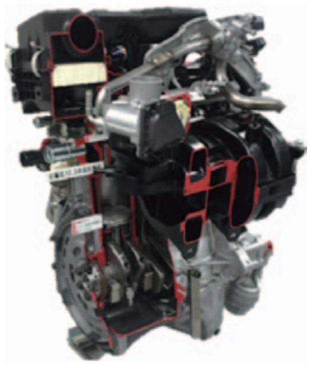

Fig. 7 Daihatsu 1KR-FE

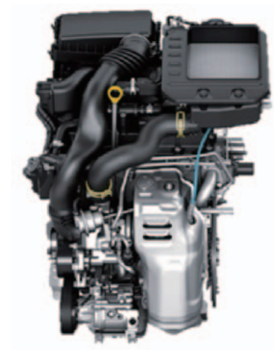

Fig. 8 Daihatsu 1KR-VET

Table 2 Main new gasoline engines in North America in 2016

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (cc)	Compression ratio	Valve train	Intake system	Fuel injection system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles equipped with this motor	Characteristics
Chrysler	Pentastar	V6	ϕ96.0×83.0	3 605	11.3 (PHEV :12.5)	DOHC 4V Roller rocker	NA	PFI	214/6 400 (PHEV :185)	355/4 000 (PHEV :311)	Jeep Grand Cherokee Pacifica Pacifica (PHEV)	Intake variable valve lift (VVL) Atkinson cycle (PHEV only), and more

finished with mirror bore coating, a cylinder head with three exhaust ports, cooled EGR, electric tumble flap control, and the Atkinson cycle, thereby raising the compression ratio from 11.2 to 12.5. At the same time, a pendulum tensioner was used to reduce loss when the integrated starter generator (ISG, a power generator with motor functions) in the auxiliary belt is operating, achieving a fuel economy of 17.2 km/L in the JC08 test cycle.

Furthermore, the VC Turbo (Fig. 4) unveiled at the Paris Motor Show in September is the first passenger vehicle engine in the world capable of varying the compression ratio from 8.0 to 14.0[2]. Starting in 2018, it is scheduled to be installed in the Infiniti destined for Europe.

2. 2. 3. Honda

The JNC engine mounted on the NSX unveiled in August (Figure 5)[2], uses technologies such as plasma spray coated cylinders, direct injection and port injection and an electric wastegate to achieve a maximum torque of 550 Nm and a maximum output of 373 kW in the V6 3.5-liter engine. The lowered engine center of gravity that contributes to improving vehicle dynamic performance has led to the adoption of a 75° V-bank angle and dry sump oil lubrication. In addition, engine rotational balancing was implemented by setting adjustment bolts were set on the flywheel and crank pulley after measuring balance to provide a superior rotational feel.

Fig. 9 Chrysler Pentastar 3.6

2. 2. 4. Subaru

Compared to previous engines, the FB20 engine mounted in the Impreza unveiled in September (Figure 6)[2] reduces noise and vibration through measures such as new designs for 80% of its parts, a weight reduction of approximately 12 kg, as well as giving the engine itself higher rigidity and additional fixing points. The adoption of direct injection raises the compression ratio from 10.5 to 12.5, achieving a fuel economy of 17.0 km/L in the JC08 test cycle.

2. 2. 5. Daihatsu

The 1KR-FE engine mounted in the Boon and Passo unveiled in April (Figure 7)[2] differs from past engines in the adoption of technologies such as dual intake ports,

Table 3 Main new gasoline engines in Europe in 2016

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (cc)	Compression ratio	Valve train	Intake system	Fuel injection system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles equipped with this motor	Characteristics
Volkswagen	EA211 evo	L4	ϕ74.5× 85.9	1 498	12.5	DOHC 4V Direct tappet	TC	DI	96/4 750–5 500	200/4 400	Golf, A3, and others	Variable geometry (VG) turbocharging, Miller cycle, 350 bar direct injector, APS-coated cylinder liner, cylinder deactivation system (ACT evo), fully variable oil pump
Porsche	DDP	H4	ϕ91.0× 76.4	1 988	9.5	DOHC 4V Direct tappet	TC	DI	220	380/1 950–4 500	718 Boxter・Cayman	Downsized turbocharger achieving +26 kW/+100 Nm over the previous H6 2.7-liter NA
	DDN	H4	ϕ102.0× 76.4	2 497	9.5	DOHC 4V Direct tappet	TC	DI	257	420/1 900–4 800	718 Boxter S・Cayman S	Turbocharger (variable geometry), downsized engine achieving +26 kW/+60 Nm over the previous H6 3.4-liter NA
Mercedes-Benz	M176	V8	ϕ83.0× 92.0	3 982	10.5	DOHC 4V Roller rocker	TC	DI	350 or	700 more	S-class	Variable valve mechanism (CAMTRONIC) Cylinder deactivation Downsized turbocharger
	M256	L6	ϕ83.0× 92.4	2 999	10.5	DOHC 4V Roller rocker	TC	DI	300 or	500 more	S-class	Turbocharger and electric compressor 48 V ISG on engine rear crankshaft Inline 6-cylinder
	M264	L4	ϕ83.0× 92.4	1 999	Undisclosed	DOHC 4V Roller rocker	TC	DI	200 or more	Undisclosed	Undisclosed	Belt-driven 48 V ISG Made modular with M176 and M256

dual injectors, and the Atkinson cycle to raise the compression ratio from 11.5 to 12.5, and achieves a fuel economy of 28.0 km/L in the JC08 test cycle through the use of anti-friction measures such as applying a new resin coat on the surface of the piston skirt.

The 1KR-VET engine mounted in the Thor, Tank and Roomy unveiled in November adds turbocharging to succeed to the 1KR-FE engine's excellent combustion characteristies resulting from the dual intake ports and dual injectors to achieve a maximum output of 72 kW and a maximum torque of 140 Nm. It also has a positive crankcase ventilation system that makes use of an ejector to suppress deposits in the engine.

3 North America

3. 1. Overview

Sales of light-duty trucks (e.g., SUVs, pickup trucks, and minivans) remain strong due to stable low gasoline prices. Although the promotion of fuel-efficient technologies at events such as motor shows has been subdued, vehicle weight reduction and engine improvement efforts are moving forward.

Fig. 10 Volkswagen EA211 1.5 TSI evo

3. 2. Automaker trends

Table 2 lists the new engines released in North America.

3. 2. 1. Chrysler

The upgraded second generation of the 3.6-liter engine (Figure 9) from the V6 3.2- to 3.6-liter lineup introduced under the Pentastar designation in 2010 is presented below. This engine, which is mounted in the Jeep Grand Cherokee raises the compression ratio from 10.2 to 11.3 through the use of cooled EGR and other technologies, with the adoption of two-stage variable valve lift (VVL) for intake hydraulic pressure realizing a maximum output of 214 kW and maximum torque of 355 Nm while re-

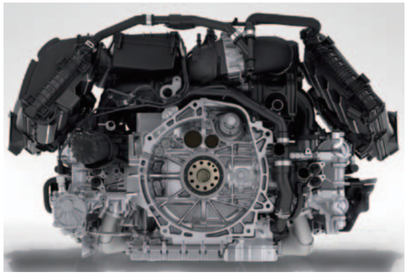

Fig. 11 Porsche DDP 2.0

Fig. 12 Porsche DDN 2.5

taining port injection. In early 2017, the Pacifica Hybrid engine for PHVs, which applies modifications such as the addition of the Atkinson cycle and a higher compression ratio (12.5) to the above engine, was announced[2].

4 Europe

4. 1. Overview

The U.S. financial crisis in 2008 and European credit crisis in 2010 caused vehicle sales in Europe to drop, but there have been signs of recovery since 2014.

Downsizing based on direct injection turbocharging is the leading trend in the European market, and enhanced fuel economy is being achieved by combining direct injection turbocharging with 48 V mild hybrids or electric turbochargers.

4. 2. Automaker Trends

All gasoline engines sold or announced in 2016 were turbocharged direct injection engines. They are listed in Table 3. In this context, Volkswagen has followed up on its 2015 EA888 Gen 3B engine (4-cylinder, 2.0-liter, mounted in the Audi A4) with the introduction of a rightsized engine aimed at improving fuel economy in the high load range.

4. 2. 1. Volkswagen

The 1.5-liter 4-cylinder EA211 TSI evo (Figure 10)[2], a rightsized engine that increases displacement to 100 cc

Fig. 13 Mercedes-Benz M176

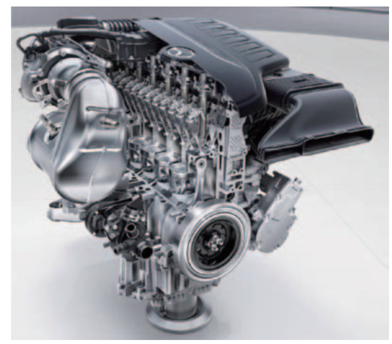

Fig. 14 Mercedes-Benz M256

Fig. 15 Mercedes-Benz M264

compared to the previous model, was presented at the 37th International Vienna Motor Symposium in April. This engine uses a turbocharger with variable turbine geometry, fuel injection increased to up to 350 bar pressure, the Miller cycle, plasma spray-coated bores, block water stop control during cooling, fully variable oil pump, a cylinder deactivation system, and other innovations to improve fuel economy by 10% over the previous model while achieving an output of 96 kW (+4 kW). The lineup also includes a 110 kW variant that incorporates different items.

4. 2. 2. Porsche

The 718 Boxster models unveiled at the International

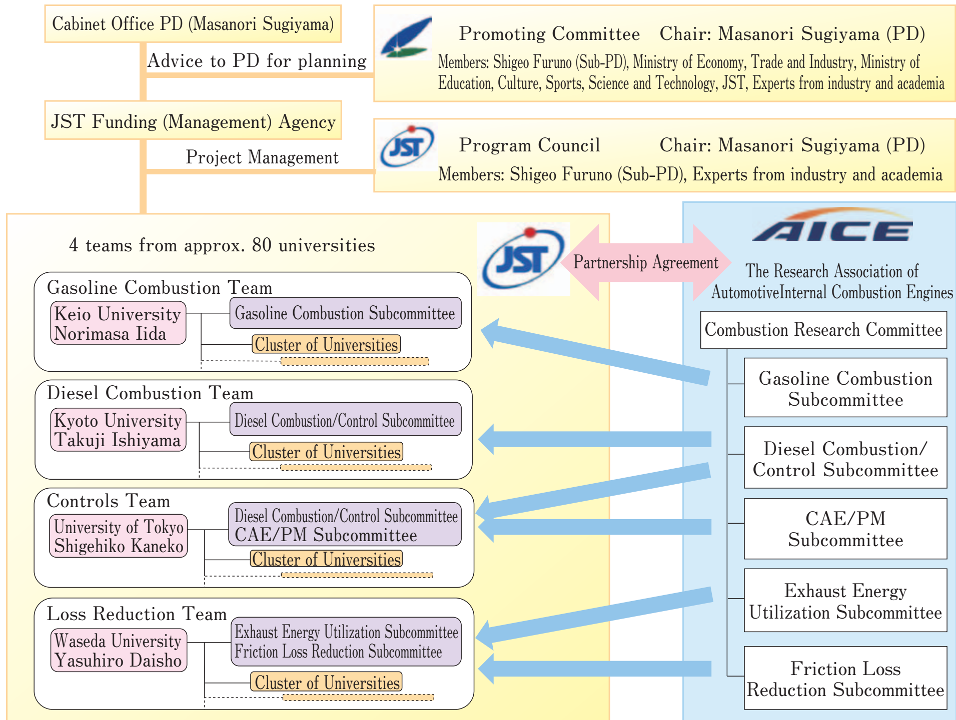

Fig. 16 Implementation Structure of the SIP Innovative Combustion Technology Program

Geneva Motor Show in March are equipped with newly developed 2.0-liter (DDP, Figure 11) or 2.5-liter (DDN, Figure 12) horizontally-opposed 4-cylinder direct injection turbocharged engines downsized from the previous horizontally-opposed 6-cylinder naturally aspirated engine. In the 2.5-liter variant (DDN), the adoption of technologies such as the variable geometry (VG) turbocharger used in the 911 emits 167 g/km of CO_2 and achieves a maximum output of 257 kW and a maximum torque of 420 NM, increases of 26 kW and 60 Nm, respectively, over the previous 3.4-liter horizontally-opposed 6-cylinder engine.

4. 2. 3. Mercedes-Benz

Three gasoline engines, the V8 4.0-liter M176 (Figure 13), the inline 6-cylinder 3.0-liter M256 (Figure 14), and the inline 4 cylinder 2.0-liter M264 (Figure 15) were announced in November. These engines all share a unified bore diameter of ϕ 83 mm and a bore pitch of 90 mm, resulting in greater production efficiency. The individual engines are described below. With features such as a displacement reduced to 700 cc and a bore pitch of 16 mm, the V8 4.0-liter M176 is a downsized variant of the previous M278 offering a 15 kW output increase and improved fuel economy through cylinder deactivation using the CAMTRONIC variable valve mechanism. The M256 is a new inline 6-cylinder engine, a variation that has been rare since the latter half of the 1990s, when automakers changed from the predominant engine length to a V configuration for 6-cylinder engines. The use of systems such as a 48 V ISG and a turbocharger with an integrated motor capable of electric turbocharging at low engine speeds are expected to achieve a maximum output of 300 kW and a maximum torque of 500 Nm. The adoption of a twin scroll turbocharger and the world's first 48 V belt-driven ISG system in the M264 is expected to achieve a maximum output of 200 kW.

5 Trends in Research

The Research Association for Automotive Internal Combustion Engines (AICE), which consists of nine Japanese automakers and two research institutes, began its activities in 2014. In addition, the Innovative Combustion Technology program was launched[(4)]. This program represents one of the ten issues identified by the Strategic Innovation Promotion Program (SIP) national project created to realize scientific and technological innovation through management that crosses ministerial and traditional field boundaries, with the Council for Science, Technology and Innovation of the Cabinet Office acting as its control center. A research framework based on government-industry-academia collaboration established under the auspices of this program will aim to raise thermal efficiency, which is limited to a maximum of about 40% in current mass-production engines, to 50%. In specific terms, the 80 or so participating universities have formed teams to research the four fields of gasoline engines, diesel engines, control, and loss reduction, with leader universities coordinating that research. The structure involves the various AICE subcommittees coordinating with, and providing support to, the individual research teams, with the Japan Science and Technology Agency (JST), which possesses research management know-how, playing a supervisory role.

An overview of the main gasoline engine-related items announced at the June public symposium[5] is presented below.

Under the title of Research and Development of Super-Lean Burn Combustion for High Efficiency Gasoline Engines, the Gasoline Combustion Team reported that it had achieved an indicated thermal efficiency of 45% in an actual single cylinder engine. Under the title of Modeling and Control to Realize Innovative Combustion Technologies, the Controls Team reported on its successful development of leading-edge measurement technology and three-dimensional PM generation trial calculations. Under the title of Research and Development on Reducing Mechanical Friction Loss through Efficient Utilization of Exhaust Energy, the Loss Reduction Team presented a report on ultra-low friction engine piston surfaces. The HINOCA software for the three-dimensional analysis of combustion in automobile engines, which is collaboratively developed by the Control and Gasoline Combustion teams, was also presented. This software is capable of analyzing the combustion cycle of a 4-cycle engine, which consists of intake, fuel injection, mixture formation discharge, flame propagation, heat loss, and exhaust as a single phenomenon, significantly reducing calculation time and allowing sophisticated combustion analysis. The possibility of applying it to corporate product development and academic R&D makes it attractive to both industry and academia, and the software is designed to grow as the latest knowledge continues to be incorporated into it over the years.

Engines will constitute the vast majority of powertrains in the automobile market for the foreseeable future, and the proportion of automobiles equipped with an engine remains high, particularly when engines for HVs, PHEVs, and range extender EVs are counted. The evolution of engines remains crucial issue in terms of addressing environmental issues, and the above research outcomes hold the promise of leading to innovative technologies.

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