GASOLINE ENGINES

1 Introduction

In October 2021, the Japanese government determined the 6th Strategic Energy Plan in cabinet to illustrate the road toward achieving carbon neutrality in 2050 and reducing greenhouse gases by 46% in 2030 (compared to 2013). This plan also targets new passenger vehicle sales consisting 100% of electrified vehicles (including hybrid vehicles) by 2035.

In July 2021, the European Commission (EC) announced the Fit for 55 policy package that aims to lower greenhouse gas emissions by 55% compared to 1990 levels. This package proposes a 55% reduction in CO_2 emissions from new vehicles by 2030 compared to 2021, followed by a 100% reduction by 2035. Europe is also considering more stringent Euro 7 emissions regulations.

In the U.S., the Biden administration was inaugurated and announced the raising of the 2026 corporate average fuel economy standard from 40.4 mpg set by the previous administration to 49 mpg. President Biden also issued an executive order targeting the active introduction of electrified vehicles and the achievement of new vehicle sales consisting 50% of plug-in vehicles (plug-in hybrid vehicles + battery electric vehicles) by 2030 (this is a target and does not have the force of law).

In China, the China Society of Automotive Engineers (China SAE) released the Energy-saving and New Energy Vehicle (NEV) Technology Roadmap 2.0. This roadmap raises the target for NEV sales (50% of new vehicle sales to be NEVs by 2035) and calls for the hybridization of all conventional energy passenger vehicles (gasoline vehicles and the like).

COP26 was held in October 2021. Participants agreed to pursue efforts to limit temperature increase at the end of the century to 1.5℃ above pre-industrial levels. The next ten years was also described as decisively important.

Against this type of social and political background, internal combustion engine (ICE) vehicles are expected to become even more fuel efficient through measures including the promotion of electrification and to generate even lower emissions.

This article introduces the main gasoline engines launched in 2021 and the research and development trends for such engines. Hybridization is progressing on a global basis. Even among the engines introduced in this article, which do not specifically mention hybrids, there are some engines that use a simple hybrid system like BSG (belt-driven starter generator). Note that, in the sections below, hybrid electric vehicles are abbreviated as HEV, plug-in hybrid electric vehicles as PHEV, and battery electric vehicles as BEV.

2 Japan

2. 1. Overview

Sales of new vehicles in Japan in 2021 reached 4.45 million units for registered and mini-vehicles (Kei-cars) combined. This was a further drop of 3.3% from 2020 when sales plummeted due to the COVID-19 pandemic, and the third successive year of decline. One of the main factors for this drop was the severe impact of semiconductor and part shortages on the production of completed vehicles. Sales of mini-vehicles alone was 1.65 million units, 3.8% lower than the previous year (2020). This figure also represents the third successive year-on-year decrease. Vehicle electrification is progressing, with HEV making up 42.8% of passenger vehicles sales, and PHEV and BEV both making up 0.9%. All these figures are higher than the previous year. In the second half of the year, total sales of HEV and other electrified vehicles exceeded sales of non-electrified vehicles, demonstrating that electrification is accelerating.

In 2021, Japanese manufacturers launched various type of engines, downsized turbo charged, variable compression ratio, high speed and high power, high efficiency for HEV, and so on.

Table 1 Main New Engines in Japan

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio (–)	Valve train	Intake system	Fuel supply system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles with this engine	Characteristics
Toyota	T24A-FTS	Inline 4	φ87.5 × 99.5	2.393	11.0	DOHC 4-valve	TC	C-DI +PFI	205/6,000	430/1,700-3,600	Lexus NX	Center direct injection, spray guide combustion, laser-clad valve seats, integrated exhaust manifold into cylinder head, close coupled transverse 3-way catalyst, multifunction valve cooling control, variable displacement oil pump, twin-scroll turbocharger
Nissan	KR15DDT	Inline 3	φ84.0 × 90.1-88.9	1.497-1.477	8.0-14.0	DOHC 4-valve	TC	S-DI	150/5,600	305/2,800-4,400	Roque, X-Trail, Qashqai	Multi-link variable compression ratio, electric intake VVT, exhaust VVT with mid-position lock, M10 spark plugs, high energy ignition (110 mJ), multifunction valve cooling control, mirror bore coating, ball bearing for #1 cam bearing, integrated exhaust manifold into cylinder head, variable displacement oil pump, turbocharger for 1050℃
Honda	J30 A	V6	φ86.0 × 86.0	2.997	9.8	DOHC 4-valve	TC	S-DI	265/5,500	480/1,400-5,000	Acura TLX, MDX	Cylinder deactivation (HYPER VTEC), oil-sealed structure VVT intake and exhaust, dry timing belt, sodium-filled exhaust valves, wear-resistant piston ring grooves, integrated cam cap and cylinder head cover, integrated exhaust manifold into cylinder head, twin-scroll single turbocharger
Subaru	FA24	Horizontal 4	φ94.0 × 86.0	2.387	12.5	DOHC 4-valve	NA	S-DI +PFI	173/7,000	250/3,700	BRZ, GR86 (Toyota)	Hollow intake valves, sodium-filled exhaust valves, variable 3-section pitch valve springs, water-cooled oil cooler
Daihatsu	WA-VE	Inline 3	φ73.5 × 94.0	1.196	12.8	DOHC 4-valve	NA	Dual PFI	64/6,000	113/4,500	Rocky, Raize (Toyota)	Common: Long stroke (SB ratio: 1.28), cooled EGR, high-tumble straight ports, dual intake ports, dual port injectors, integrated exhaust manifold into cylinder head WA-VE: Dual passage cooling system
	WA-VEX	Inline 3	φ73.5 × 94.0	1.196	12.8	DOHC 4-valve	NA	Dual PFI	60/6,000	105/4,500	Rocky, Raize (Toyota)	

Note 1: VVT: variable valve timing (phase) system, VVL: variable valve lift system
Note 2: S-DI: side layout direct injection, C-DI: center layout direct injection
Note 3: EIVC: early intake valve closing, LIVC: late intake valve closing
Note 4: Power and torque values are cited from sources that are listed at the end of this article. These values may differ from the catalog values of the vehicles in which the engines are installed.

2. 2. Trends of Each Manufacturer

Table 1 lists the new gasoline engines launched by manufacturers in Japan in 2021, which are summarized below.

(1) Toyota

Toyota launched the 2.4-liter inline 4-cylinder naturally aspirated T24A-FTS engine (Fig. 1), which was installed on the Lexus NX350. This engine is a downsized replacement for a 3.5-liter V6 naturally aspirated engine and was developed with the aims of increasing power, fuel economy, and environmental performance. It carries on the Toyota New Global Architecture design concept

Fig. 1 Toyota T24A-FTS

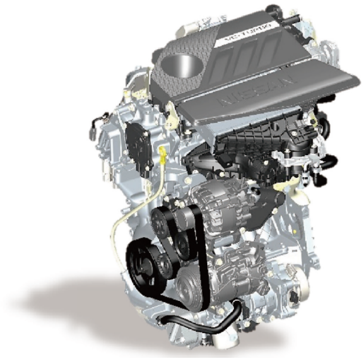

Fig. 2 Nissan KR15DDT

from the previous model and adopts a new center layout direct injection system alongside existing features such as a long stroke and high-speed combustion. The engine adopts a spray guide combustion system that further retards the catalyst warm up combustion phase to promote catalyst temperature rise. The catalyst itself is located closer to the turbine outlet for improved warm-up performance. Exhaust gases are passed through a waste gate valve to the center of the catalyst, making effective use of exhaust gas heat to warm up the catalyst. The engine also adopts a highly responsive twin scroll turbocharger. Each part of this turbocharger was refined to further enhance efficiency and increase acceleration response. These technologies help to realize excellent driving performance and fuel economy (maximum thermal efficiency: 38%) and environmental performance that complies with California's SULEV 30 emissions standards.

(2) Nissan

Nissan launched the 1.5-liter inline 3-cylinder turbocharged KR15DDT engine (Fig. 2), which features a multi-link variable compression ratio mechanism and was installed on the X-Trail and Qashqai. Although this variable compression ratio mechanism has already been adopted on the 2.0-liter KR20DDET engine, the KR15DDT combines this mechanism with low-pressure cooled EGR (LP-EGR) to further improve fuel economy. This LP-EGR system widens the high compression ratio operating region of the engine by improving knocking performance. Together with the effects of EGR, the result is more impressive fuel economy. To expand the EGR region and increase control accuracy, an EGR throttle valve was installed upstream of the EGR inlet port. The accuracy of EGR control is improved by maintaining the pressure difference before and after the EGR valve, enabling a

Fig. 3 Honda J30A

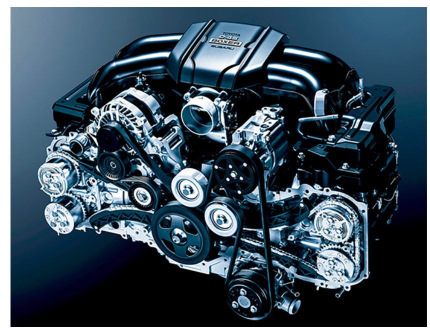

Fig. 4 Subaru FA24

maximum EGR rate of 20%. In addition, to improve combustion stability when EGR is applied, the intake ports and pistons were designed to increase tumble flow. These technologies help to substantially expand the low fuel consumption region of the engine. This engine is combined with BSG type mild HEV or Nissan's series HEV e-POWER.

(3) Honda

Honda launched the 3.0-liter V6 turbocharged J30A engine, which was installed in the North American-specification Acura TLX (Fig. 3). This engine was particularly designed for compactness as well as power and environmental performance. It features a low height cylinder head, an integrated cam bearing cap and cylinder head cover, and a turbocharger installed above the transmission. Despite its dual overhead cam (DOHC) layout, this engine is the same size or smaller than Honda's single overhead cam (SOHC) 3.5-liter V6 naturally aspirated engine. It also features a cylinder deactivation system to further improve fuel economy. The valve deactivation mechanism adopts the HYPER VTEC system that uses the tappet to switch operation, which is also adopted on Honda's motorcycles. The twin-scroll single turbocharger is designed to guide the exhaust gas collected from each cylinder bank to each scroll. This system minimizes tur-

Fig. 5 Daihatsu WA-VEX

bo lag and improves throttle response, while also achieving maximum torque from 1,400 rpm.

(4) Subaru

Subaru launched the 2.4-liter horizontally opposed naturally aspirated FA24 engine for sports cars (Fig. 4), which was installed on the Subaru BRZ and Toyota GR86. This engine was developed with the aims of increasing power by expanding displacement from the previous 2.0-liter FA20 engine while also reducing weight and realizing excellent environmental performance. Larger displacement was achieved by increasing the bore size. As a result, power was increased from 152 to 173 kW compared to the previous model. Also, valve diameter was expanded and intake/exhaust system were optimized. In order to achieve high rpm and high power, the weight reduction and increasing stiffness of the main moving parts such as the pistons, connecting rods, and crankshaft were done. To reduce the moment of inertia around the crankshaft rotational axis, the weight of parts such as the crankshaft pulley was substantially reduced. The moment of inertia of the piston-crankshaft moving system, which includes the crankshaft pulley, was reduced by 19% compared to the previous model despite the larger displacement. Furthermore, to realize both the typical low-slung styling of a sports car and excellent pedestrian protection performance, parts layout was devised. The height of engine is lower than the previous model.

(5) Daihatsu

Daihatsu launched the 1.2-liter inline 3-cylinder naturally aspirated WA-VE and VEX engines (Fig. 5) for installation on the Rocky. The WA-VE engine is for gasoline vehicles and the WA-VEX engine is for HEV. These engines were developed in accordance with the Daihatsu New Global Architecture (DNGA) design concept and each technical elements was refined. These engines incorporates the long stroke design, high compression ratio, and adoption of cooled EGR, which are the cornerstone technologies of recent highly efficient naturally aspirated engines. In these engines, the stroke/bore ratio was further increased to 1.28, helping to further improve fuel economy and increase compactness. Combustion performance was enhanced by the adoption of high tumble ports, compact combustion chambers, and refined dual port injectors. These injectors further decrease spray penetration to minimize the amount of fuel adhesion on the port walls. The size of the engines was kept to the equivalent of a 1.0-liter engine by the long stroke design and the adoption of an devised layout. The WA-VEX engine for HEV achieves a maximum thermal efficiency of 40% and is combined with Daihatsu's series e-SMART Hybrid system.

3 The U.S.

3. 1. Overview

In 2021, new vehicle sale in the U.S. was a figure of 14.93 million units. Although 3.1% higher than the previous year (2020), sales have yet to recover to the pre-COVID-19 pandemic levels of 17 million vehicles. Despite the clear signs of an economic rebound, the semiconductor shortage restricted production and hampered the sales recovery. HEV made up 5.4% of total sales, PHEV 1.2%, and BEV 2.9%. The market share of each of these

Table 2 Main New Engines in the U.S.

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio (−)	Valve train	Intake system	Fuel supply system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles with this engine	Characteristics
GM	LT6 (Not released)	V8	φ104.25 × 80	5.463	12.5	DOHC 4-valve	NA	S-DI	500/8,400	623/6,300	Chevrolet Corvette Z06	Flat-plane crankshaft, titanium intake valves, sodium-filled exhaust valves, dual coil valve springs, forged aluminum pistons, forged titanium connecting rods, variable intake plenum chambers, direct injectors installed on exhaust side, 6-stage dry sump lubrication system

Fig. 6 GM LT6

types of electrified vehicles roughly doubled from the previous year.

3. 2. Trends of Each Manufacturer

Table 2 lists the new gasoline engines launched or announced by manufacturers in the U.S. in 2021, which are summarized below.

(1) GM

GM developed the 5.5-liter V8 naturally aspirated LT6 engine (Fig. 6), which is planned to be installed in the Chevrolet Corvette Z06. The features of this engine are high rpms and power, which are specifically intended to realize sporty performance by generating maximum power of 500 kW at 8,400 rpm. The engine adopts a flat-plane crankshaft, short stroke, forged pistons, and forged titanium connecting rods to handle the high rpms and power generated by the rotating and moving systems. Titanium intake valves, sodium-filled exhaust valves, and dual coil valve springs also help to increase the rpms and power of the engine. The intake system features an independent twin throttle system for each cylinder bank. This is a variable intake system that controls the link to the plenum chamber of each bank in accordance with the driving conditions. Fuel injection is carried out by a 35 MPa direct injection system with the injectors installed below the exhaust ports. This engine also adopts a new 6-stage dry sump lubrication system.

4 Europe

4. 1. Overview

In 2021, new vehicle sales in Europe was 9.7 million units (including the 26 countries in the EU and excluding Malta), 2.4% lower than the previous year (2020). This was the second consecutive year-on-year decline and reflects the impact of production limitations caused by urban lockdowns during the COVID-19 pandemic and shortages of semiconductors and parts. Vehicle electrification is making progress, with HEV accounting for 19.6% of total sales, PHEV 8.9%, and BEV 9.1%. The market share of these electrified vehicles increased between 60 and 70% compared to the previous year. HEV are gaining market share as a replacement for diesel vehicles, and sales of plug-in vehicles such as PHEV and BEV are being supported by substantial government incentives. In contrast, the market share of diesel vehicles fell to 19.6%. Looking at the specific sales figures, sales of HEV exceeded those of diesel vehicles for the first time.

In the case of gasoline engines, the refinement of turbocharged engines is making progress. Manufacturers are focusing on expanding the lambda=1 (stoichiometric air-fuel ratio) engine operating region in anticipation of the more stringent Euro 7 emissions standards.

4. 2. Trends of Each Manufacturer

Table 3 lists the new gasoline engines launched by manufacturers in Europe in 2021, which are summarized below.

Table 3 Main New Engines in Europe

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio (−)	Valve train	Intake system	Fuel supply system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles with this engine	Characteristics
Mercedes-Benz	M254 2.0 L	Inline 4	φ83.0 × 92.0	1.999	TBD	DOHC 4-valve	TC + electric SC	C-DI	200/6,000	400/1,600-3,000	C300	Intake cam shifting VVL (CAMTRONIC), wire arc spray coated cylinders (NANOSLIDE), trumpet-shape honing (CONICSHAPE), electric water pump, electric thermostat, twin-scroll turbocharger (with scroll communication), electric supercharger
	M254 1.5 L	Inline 4	φ78.0 × 78.2	1.494	10.5	DOHC 4-valve	TC	C-DI	150/5,800	300/1,800-4,000	C200	TBD
Volvo	VEP GEN3 LP	Inline 4	φ82.0 × 93.2	1.969	12.0	DOHC 4-valve	TC	C-DI	145/4,750	300/1,500-4,500	V60	EIVC Miller cycle, variable geometry turbocharger (VGT), center direct injection, fuel pressure: 45 MPa, crankshaft-driven fuel pump, integrated exhaust manifold into cylinder head, entire-region lambda=1 combustion
Ferrari	F163	V6	φ88.0 × 82.0	2.992	9.4	DOHC 4-valve	TC	C-DI	488/8,000	740/6,250	296GTB	120 V-bank angle, exhaust inside banks, turbochargers installed inside banks, opposite-direction rotation of turbochargers in left and right banks, center direct injection

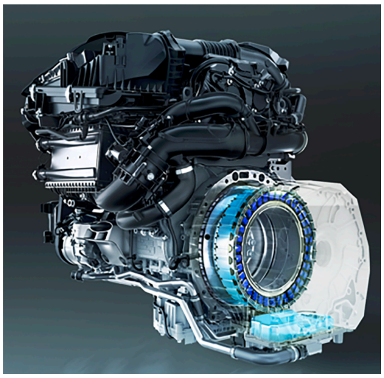

Fig. 7 Mercedes-Benz M254

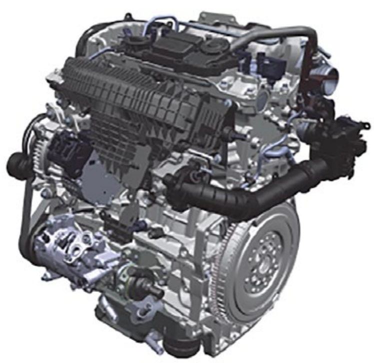

Fig. 8 Volvo LP (Third Generation VEP)

(1) Mercedes-Benz

The M254 is a series of inline 4-cylinder turbocharged engines (Fig. 7) installed on the C Class. Although this series consists of 2.0- and 1.5-liter variants, this section focuses on the 2.0-liter engine. This engine is the 4-cylinder version of the 3.0-liter inline 6-cylinder M256 engine already on the market. Designed assuming the adoption of a 48V system, it shares many technologies with the M256, including the same bore × stroke dimensions. The cam shifting VVL system CAMTRONIC is adopted and the Miller cycle operation is performed at partial loads. Also, charging system is combined one which consists of a twin-scroll turbocharger and an electric supercharger. This twin-scroll turbocharger is equipped with a passage that links between the two scrolls, which can be opened and closed to select either an impulse or constant pressure turbocharging mode depending on the driving conditions. This charging system expands the lambda=1 combustion region while enabling higher power performance. This engine is combined with a 48V P1 HEV system, which includes a motor (15 kW/180 Nm) installed between the engine and transmission.

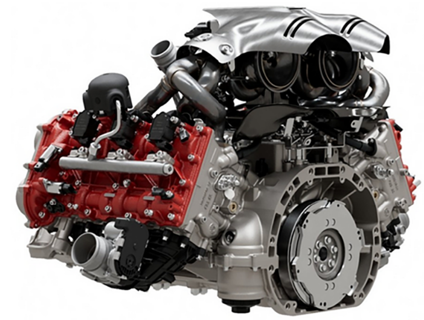

Fig. 9 Ferrari F163

(2) Volvo

The Volvo Environmental Petrol (VEP) series of gasoline engines is currently centered on its third generation. In addition to the existing standard type (MP) and high power type (HP), Volvo has also developed a new Miller cycle type LP engine (Fig. 8). This engine is installed on the V60. The LP engine was developed with the aims of improving fuel economy and realizing entire-region lambda=1 combustion to achieve low emissions. The adoption of the Miller cycle makes it more difficult to realize both low-end torque and high-end power. Therefore, this engine realizes favorable torque characteristics by adopting a variable geometry turbocharger (VGT). As a result, maximum torque of 300 Nm is produced from 1,500 rpm, with maximum power of 145 kW. Brake specific fuel consumption (BSFC) is lower than the MP engine in all operating regions, and a 4-to-5% improving in fuel economy was achieved in the Worldwide Harmonized Light Vehicles Test Cycle (WLTC).

(3) Ferrari

Ferrari launched the 3.0-liter V6 turbocharged F163 engine (Fig. 9), which is installed on the midship 296 GTB PHEV. This engine generates power of 488 kW. Total system power including the motors is as high as 610 kW. The engine is distinguished by the wide 120-degree angle of its V banks, which incorporate two turbochargers. The rotors of turbochargers in the left and right banks rotate in opposite directions for more symmetrical performance. The fuel injection system is a 35 MPa center direct injection system. The motors of the PHEV system are installed between the engine and the 8-speed dual-clutch transmission (DCT). This clutch can be used to disconnect the motors from the engine. These 122 kW/315 Nm motors are combined with a 7.45 kWh battery to enable an EV mode range of 25 km.

Table 4 Main New Engines in Asia

Manufacturer	Engine model	Cylinder arrangement	Bore × stroke (mm)	Displacement (L)	Compression ratio (–)	Valve train	Intake system	Fuel supply system	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Main vehicles with this engine	Characteristics
BYD	BYD472QA	Inline 4	φ72.0 × 92.0	1.498	15.5	DOHC 4-valve	NA	PFI	81/6,000	135/4,500	Qin Plus	High compression ratio (15.5), long stroke (SB ratio: 1.28), LIVC Atkinson cycle, cooled EGR, intelligent heat management, DLC-coated pistons, high-energy ignition, integrated exhaust manifold into cylinder head, electric water pump, electric thermostat, split head/block cooling, variable displacement oil pump
SAIC	20 A4 E	Inline 4	φ82.5 × 92.9	1.988	11.5	DOHC 4-valve	TC	S-DI	172/5,000	360/1,500-3,500	iMAX8	EIVC Miller cycle, intake cam shifting VVL, integrated exhaust manifold into cylinder head, variable displacement oil pump
Hyundai	Smartstream G 1.5 T-GDI	Inline 4	φ71.6 × 92.0	1.482	10.5	DOHC 4-valve	TC	S-DI	118/5,500	253/1,500-3,500	i30, Ceed (Kia)	Continuous variable valve duration (CVVD), LIVC Atkinson cycle, LP-EGR, multifunction valve cooling control, high energy ignition (120 mJ), integrated exhaust manifold into cylinder head, variable displacement oil pump
	Smartstream G 1.0 T-GDI	Inline 3	φ71.0 × 84.0	0.998	10.5	DOHC 4-valve	TC	S-DI	88.3/6,000	200/2,000-3,500	i30, i20, Picanto (Kia), Rio (Kia)	Same as described above
	Smartstream G 1.2 DPI	Inline 4	φ71.0 × 75.6	1.197	11.0	DOHC 4-valve	NA	Dual PFI	61.7/6,000	117.6/4,200	i20, Picanto (Kia), Rio (Kia)	Dual port injectors, cooled EGR, multifunction valve cooling control, intake VVT with mid-position lock integrated exhaust manifold into cylinder head
	Smartstream G 1.0 DPI	Inline 3	φ71.0 × 84.0	0.998	11.0	DOHC 4-valve	NA	Dual PFI	49.3/5,500	96.1/3,750	Casper, Picanto (Kia)	Same as described above

5 Asia (Excluding Japan)

5. 1. Overview

In 2021, vehicle sales in China, the largest market in the world reached 26.28 million units, 3.8% higher than the previous year (2020). This was the first year-on-year increase after consecutive decreases from 2018. Sales of new energy vehicles NEV reached 3.52 million units, a market share of 13.4% and 2.6 times higher than the previous year.

Chinese manufacturers appear to be emphasizing thermal efficiency and have been developing dedicated HEV engines with a particular emphasis on this aspect in recent years. Korean manufacturers are taking a thorough approach to modularization and are developing engines that can be deployed on a global basis.

5. 2. Trends of Each Manufacturer

Table 4 lists the new gasoline engines launched or announced by manufacturers in Asia (excluding Japan) in 2021, which are summarized below.

(1) BYD

The 1.5-liter inline 4-cylinder naturally aspirated 472QA engine is installed in the Qin Plus PHEV. Developed with an emphasis on thermal efficiency, BYD announced that it achieves an efficiency of 43% which is top level as mass production engines. The main technologies adopted in this engine to increase thermal efficiency include a high compression ratio (15.5), long stroke (stroke/bore ratio: 1.28), Atkinson cycle, and cooled EGR. Combustion with large amount of EGR is realized by the adoption of high tumble ports and pistons that maintain the tumble flow. The cooling system combines heat management technologies such as an electric water pump, electric thermostat, and split head/block cooling to shorten the warm-up time and enhance fuel economy. This engine generates power of 81 kW and be combined with PHEV system which includes 132 or 145kW electric motor.

(2) SAIC

The 2.0-liter inline 4-cylinder 20A4E engine is installed on the iMAX8. It adopts the Miller cycle with a high compression ratio of 11.5. This approach expands the lambda=1 combustion region while realizing high power performance of 172 kW and an excellent thermal efficiency of 39.5%. The intake side adopts a cam shifting type VVL. Pumping-loss is reduced by switching to a narrow

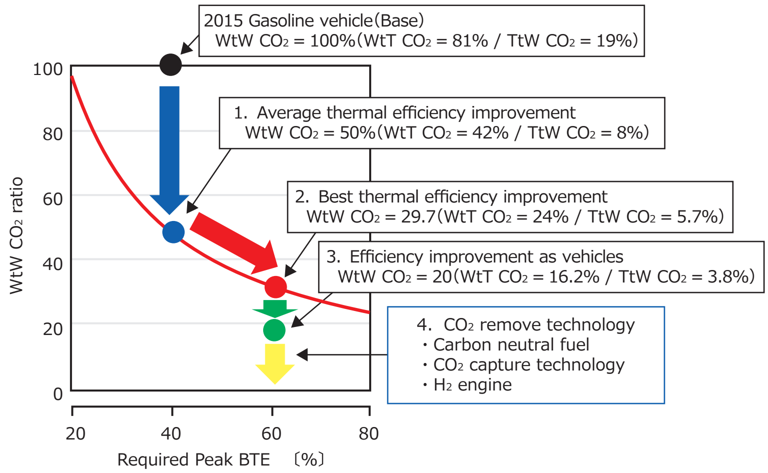

Fig. 10 Scenario to Carbon Neutrality

opening duration lift curve under partial loads to improve fuel economy. Other features include an offset crankshaft, smaller diameter main crank journal, variable displacement oil pump, and other friction reducing technologies that lower friction by 32% compared to SAIC's previous 2.0-liter engine.

(3) Hyundai

Hyundai has developed the 1.5-liter inline 4-cylinder Smartstream G 1.5T-GDI engine and a 1.0-liter inline 3-cylinder engine in the same series. These engines were launched in the European market and are installed on models such as the Hyundai i30. The engines were developed under a modular concept with many common technologies. The different displacements were realized by changing the number of cylinders and the bore × stroke dimensions. The distinguishing technological features of these engines are the adoption of continuous variable valve duration (CVVD) and LP-EGR. CVVD is a mechanism that continuously changes the opening duration of the intake valves, enabling the Atkinson cycle under partial loads to enhance fuel economy and increasing power performance by optimal control of the opening duration under high loads. In the LP-EGR system, the EGR throttle valve is installed upstream of the EGR inlet to intake, enabling the application of large amount of EGR (maximum of approximately 20%) and improving control accuracy. Also, enhanced combustion is realized by intensifying tumble flows and adopting high energy ignition (120 mJ). In addition, multifunction valve cooling management is adopted.

The 1.2-liter inline 4-cylinder naturally aspirated Smartstream G 1.2 DPI engine and 1.0-liter inline 3-cylinder engine in the same series have been installed on models such as the Hyundai i20. These engines were also developed under the same modular concept. Common technologies include the bore dimension, compression ratio, cooled EGR, dual-port injectors, multifunction valve cooling management, and VVT with a mid-position lock mechanism.

6 Trends in Research and Development

6.1. Government-Industry-Academia Collaboration

(1) Research Association of Automotive Internal Combustion Engines (AICE)

Under the slogan of "environmentally friendly combustion engines for ultimate thermal efficiency and zero emissions," AICE conducts projects with participants from many companies and research institutes. At the Autumn Congress of the Society of Automotive Engineers of Japan (JSAE) in 2021, AICE announced its carbon neutral technical scenario for ICE vehicles. This scenario aims to achieve a reduction in CO_2 of at least 80% through hybridization to enhance average thermal efficiency and the development of more advanced ICE to raise the maximum thermal efficiency of engines and increase vehicle efficiency. Futhermore, by sustainable fuels and CO_2 capture and reuse technologies, the carbon neutral at 2050 is aimed.

(2) Zero Emission Mobility Power Source Research Consortium

This consortium started in 2020 and consists primarily of universities. It is carrying out projects with the aim of realizing zero emission mobility. In collaboration with

AICE, the research seeds of the consortium are matched to the needs of AICE to select themes. Currently, 19 research themes are being conducted across fields including combustion control, emissions treatment, and structures.

(3) Japan Automotive Model-Based Engineering Center (JAMBE)

In July 2021, JAMBE began joint projects with the participation of ten Japanese companies and the Japan Automobile Research Institute (JARI). The objective of JAMBE is to contribute to the international competitiveness of the Japanese automotive industry by widely disseminating and further developing the "SURIAWASE 2.0" model-based development technology. This project will continue in the future in collaboration with AICE.

6. 2. Research Papers

This section briefly describes the 2021 JSAE Awards-winning papers that are closely related to gasoline engines.

(1) Control of Compression Ignition Using High-Pressure Multiple Gasoline Injection

The narrow engine operating region is an issue of homogeneous charge compression ignition (HCCI) combustion, which is capable of realizing both low fuel consumption and emissions. In this paper, Ito et al. proposes a combustion technology concept that controls the temperature and fuel concentration inside the cylinder by multiple injections during the compression stroke to expand the operating region of the engine and to control ignition.

(2) TWC Performance and Reaction Mechanism of Rh Catalyst Reduced at High Temperature

In this paper, Tsuda et al. describes durability tests under an environment reflecting the real-world operating conditions of gasoline engines, and then uses various analytical techniques to examine the deterioration characteristics of Rh catalysts and the effects on reactions. Based on the results of this analysis, the paper demonstrates the potential for improving the performance of Rh catalysts when Rh particles are arranged in an optimum structure by processing under high-temperature reduction conditions.

6. 3. Research into Carbon Neutral Fuels

Hydrogen and e-fuels synthesized from renewable energy sources are attracting attention as means of achieving carbon neutrality using ICE.

Hydrogen engines have the merits of a similar combustion system and parts composition to gasoline engines and a close affinity with the existing automotive industry. For these reasons, research is being actively carried out. Toyota Motor Corporation is making progress in hydrogen engine research, and is carrying out field tests by entering hydrogen engine vehicles in Super Taikyu Series races. Parts suppliers are also developing key components such as hydrogen injectors and engine systems. In the motorcycle field as well, four Japanese companies have also started examining the feasibility of joint development.

E-fuel has the major merit of reducing the CO_2 emissions of cars already on the road. Many research institutes and companies are carrying out research into this topic.

Although major issues must be resolved before such carbon-neutral fuels can be practically adopted, it is hoped that research and development will accelerate to realize this goal as quickly as possible.

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