DIESEL ENGINES

1 Introduction

With Japan holding back on introducing particulate number (PN) regulations, no diesel passenger vehicles have yet been launched that satisfy the 2030 fuel economy standards under the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). Despite this situation, some vehicles debuted in 2022 that fulfill 90% of these standards. In contrast, some heavy-duty vehicles were launched this year that satisfy the fuel economy standards for 2025.

In Europe, the Euro 7 regulations were proposed in November 2022. Usually, these regulations differentiate between passenger and heavy-duty vehicles. However, this proposal lays down uniform regulations, far more stringent values to be satisfied, and is based around on-road tests. Manufacturers will be required to guarantee the environmental friendliness of engines under all driving conditions, as well as under a wide range of environments and loads. Other requirements in the proposal include restrictions on additional pollutants, an extension to the minimum service life or driving distance of engines, and the installation of emissions monitoring systems (onboard monitoring (OBM)). At the same time, the Council of the European Union (EU) has decided to adopt more stringent CO_2 emissions standards for new passenger and light-duty commercial vehicles, and requires all new vehicles launched from 2025 to emit zero CO_2. However, the same regulations also contain language about synthetic fuels (i.e., e-fuels). After discussions with its stakeholders, the European Commission (EC) will likely make a proposal about the registration of vehicles capable of being driven on carbon-neutral fuels alone.

In the U.S., in December 2022, the Environmental Protection Agency (EPA) came to a final decision about the new standards for reducing emissions from heavy-duty vehicles to be adopted from 2027. These prospective emissions standards are a partially relaxed version of the omnibus regulations for heavy-duty vehicle NOx emissions adopted by the California Air Resources Board (CARB) in August 2020. Federal air pollution standards for heavy-duty trucks were updated for the first time in over twenty years. These standards are 80% more stringent that current standards and incorporate a new light load transient cycle (LLC), as well as extensions to the minimum service life or driving distance of engines. In addition, a certain proportion of new vehicles sold in California from the 2024 model year are required to be advanced clean trucks (ACTs) defined as zero or near-zero emission vehicles (NZEVs) such as plug-in hybrid electric vehicles (PHEVs).

With this background, this article mainly describes the characteristics and summarizes the new diesel engines announced or launched in 2022.

2 Trends inside Japan

2. 1. Overview

(1) Diesel Engines for Passenger Vehicles

Mazda Motor Corporation launched the inline 6-cylinder 3.3-liter SKYACTIV-D 3.3 T3 engine for SUVs. Nissan Motor Co., Ltd. launched the Caravan equipped with the 2.4-liter 4N16 engine manufactured by Mitsubishi.

(2) Diesel Engines for Commercial Vehicles

Although no new engines were launched onto the market in 2022, Isuzu Motors Limited refined the existing 10.8-liter GH11 heavy-duty truck engine from UD Trucks and launched it as the 9.8-liter 6UZ1 engine.

2. 2. New Engine Characteristics (Table 1)

(1) Mazda T3 (SKYACTIV-D 3.3) (Fig. 1)

The T3 engine was developed with a larger 3.3-liter displacement with the aim of realizing ideal combustion characteristics. While producing powerful torque for large SUVs, this engine is clean enough to satisfy Japan's real driving emissions (RDE) regulations without a NOx aftertreatment system. It adopts steel pistons and a variable oil pump to reduce friction, and realizes 8 to 10%

Table 1 New Engine Specifications

Region	Application	Manufacturer	Engine model	Cylinder arrangement	Bore diameter × stroke (mm)	Total displacement (L)	Compression ratio	Max. output (kW/rpm)	Max. torque (Nm/rpm)	Characteristics
Japan	Passenger vehicles	Mazda	T3 -VPTH T3 -VPTS	L6	86.0 × 94.2	3.283	15.2	187/3,750 170/4,000 –4,200	550/1,500 –2,400 500/1,500 –3,000	3.3 -liter inline 6 -cylinder, distribution controlled partially premixed compression ignition (DCPI), two-stage egg-shaped combustion chambers, steel pistons, fuel injection pressure: 350 MPa, single VG turbocharger, HP and LP EGR, variable pressure and capacity oil pump, 48 V mild hybrid system
		Nissan	4 N16	L4	86.0 × 105.0	2.439	15.1	97/3,250	370/2,000	Balancer shaft, DPF with SCR function, two-stage SCR and urea injection system
	Commercial vehicles	UD Truck	GH11 TD GH11 TC2 GH11 TC1 GH11 TB2 GH11 TB1 GH11 TA2 GH11 TA1	L6	123 × 152	10.836	—	339/1,700 316/1,600 309/1,600 294/1,600 287/1,600 272/1,600 265/1,600	2,250/1,200 2,000/1,200 1,900/1,200 2,000/1,200 1,750/1,200 2,000/1,200 1,750/1,200	New injection system utilizing the advantages of both unit injectors and the common rail system, modified combustion chamber shape, low-viscosity engine oil, some specifications exceed 2015 heavy-duty vehicle fuel economy standards by 10 %, satisfies 2025 fuel economy standards
		Isuzu	6 UZ1 -TCS 6 UZ1 -TCC	L6	120 × 145	9.839	18.0	279/1,800 265/1,800	1,814/1,000 –1,200 1,567/900 –1,600	Main vehicle models exceed 2025 fuel economy standards by 5 %
Outside Japan	Passenger vehicles	GM	Duramax 3.0 L Turbo-Diesel I-6 LZ0	L6	84 × 90	2.992	15.0	227/3,750	671/2,750	Power increased by 10 %, torque increased by 7.6%, revised combustion chamber shape, steel pistons, optimized turbocharger compressor, new fuel injectors, improved temperature control function
	Commercial vehicles	Scania	DC13 176 175 174 173	L6	130 × 160	12.74	23.0	309/1,800 338/1,800 368/1,800 412/1,800	2,300/900 –1,280 2,500/900 –1,290 2,650/900 –1,320 2,800/900 –1,400	This engine was launched in November 2021. Scania twin SCR system, DOHC, compression ratio: 23, peak firing pressure: 25 MPa, compatible with HVO/FAME
		Mercedes-Benz	OM471	L6	132 × 156	12.8	20.3	310/1,600 330/1,600 350/1,600 375/1,600 390/1,600	2,100/1,100 2,200/1,100 2,300/1,100 2,500/1,100 2,600/1,100	Third generation, improved combustion, compression ratio: 20.3, peak firing pressure: 25 MPa, two available turbochargers (one emphasizing fuel economy that is manufactured in-house and one emphasizing high power), low-viscosity oil, oil pressure control valve, control using predictive SCR temperature model
		FPT Industrial	XCursor13	L6	135 × 150	12.9	—	338/1,650 〃 368/1,650 〃 397/1,65 〃 426/1,65 〃 442/1,900	2,300/770 2,500/820 2,400/795 2,600/843 2,500/910 2,700/956 2,600/940 2,800/978 2,850/1,100	Multi-fuel single-base engine, electronically controlled VG ball bearing divided-flow turbocharger, lower friction, adoption of CGI cylinder head and block, peak firing pressure: 27 MPa, fuel injection pressure: 250 MPa

Table 1 New Engine Specifications (cont.)

Region	Application	Manufacturer	Engine model	Cylinder arrangement	Bore diameter × stroke (mm)	Total displacement (L)	Compression ratio	Max. output (kW/rpm)	Max. torque (Nm/rpm)	Characteristics
Outside Japan	Commercial vehicles	Cummins	X10	L6	—	10	—	239/— 336/—	1,356/— 2,237/—	Fuel-agnostic engine platform, DOHC, improved combustion, high-efficiency engine braking, lower friction, electronically controlled waste gate turbocharger, 48 V alternator, heater for aftertreatment system, twin-dosing and dual SCR
		Navistar	International® S13	L6	130 × 160	12.74	23.0	276/1,800 298/1,800 298/1,800 321/1,800 336/1,800 350/1,800 384/1,800	1,695/900 1,966/900 2,508/900 2,101/900 2,373/900 2,373/900 2,508/900	Developed integrated powertrain system, compression ratio: 23, no cooled EGR, peak firing pressure: 25 MPa, fuel injection pressure: 180 MPa, DOHC, fixed-geometry turbocharger, dual SCR, continuously regenerating DPF

Fig. 1 Mazda T3 (SKYACTIV-D3.3)

Fig. 2 Nissan 4N16

better specific fuel consumption than the previous 2.2-liter engine. This engine features two-stage egg-shaped combustion chambers and high-response injectors that optimize the quantity and timing of injection. These technologies prevent contact between high-temperature burned gas and subsequent injection sprays. Each stage of the multi-injection strategy is designed to realize distribution-controlled partially premixed compression ignition (DCPCI) that forms sufficiently lean premixed gas, which has the effect of extending premixed combustion to the practical medium-load range. Despite the larger displacement, the maximum mean effective pressure of the engine was restricted to enable the application of EGR in sufficient quantities up to high loads, thereby greatly lowering NOx. In addition to these refinements, the engine is paired rationally with a 48 V mild hybrid system and highly efficient 8-speed automatic transmission. Mazda's unique cooperative control technology also contributes to a further improvement in fuel efficiency.

(2) Nissan 4N16 (Fig. 2)

This engine is installed in the Nissan Caravan and features higher combustion efficiency and lower frictional resistance to deliver high torque characteristics that help to realize smooth acceleration and a substantial improvement in fuel efficiency. It is also equipped with a new balancer shaft that reduces booming noise caused by engine vibration and ensures a quieter ride. The exhaust aftertreatment system features a diesel particulate filter (DPF) with a selective catalyst reduction (SCR) function, as well as a two-stage SCR and urea injection system to enhance NOx purification performance.

(3) UD Trucks GH11 (Fig. 3)

This engine realizes excellent environmental performance by improving combustion through a new injection system that utilizes the advantages of both unit injectors and the common rail system, and a modified combustion chamber shape, as well as by adopting low-viscosity engine oil to reduce friction. Paired with a new ECO+

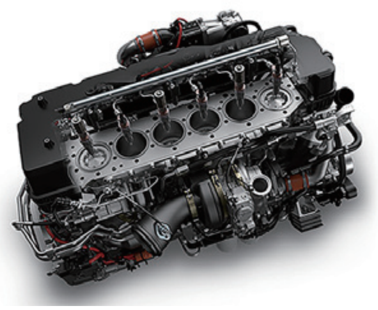

Fig. 3 UD Truck GH11

Fig. 4 Isuzu 6UZ1

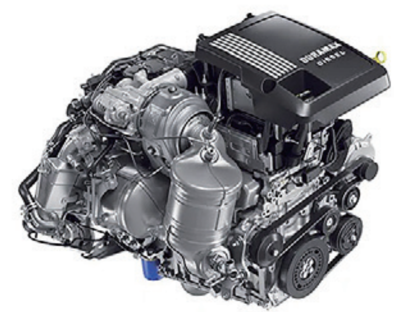

Fig. 5 GM Duramax 3.0 L Turbo-Diesel I-6 LZ0

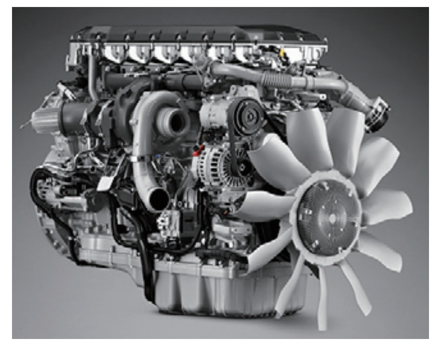

Fig. 6 Scania DC13

mode for vehicle operation, the ESCOT-Ⅵ 12-speed automated manual transmission (AMT), and low rolling resistance tires, this engine exceeds the 2015 heavy-duty vehicle fuel economy standards by 10% and satisfies 2025 fuel economy standards.

(4) Isuzu Motors 6UZ1 engine (Fig. 4)

This engine features a turbocharger with optimized specifications and other improvements extending to the structural systems and fuel injectors. As a result, it realizes low fuel consumption by targeting efficiency at frequently used practical engine speeds. Combined with low rolling resistance tires, the main vehicle models using this engine exceed the 2025 fuel economy standards by 5%.

3 Trends outside Japan

3. 1. Overview

(1) Diesel Engines for Passenger Vehicles

General Motors (GM) launched and adopted the new Duramax 3.0 L LZ0 engine for pick-up trucks.

(2) Diesel Engines for Commercial Vehicles

Enhanced and new engines were launched factoring in compliance with CO_2 regulations and Euro 7 in Europe, as well as CARB and EPA regulations in the U.S. This year also saw a series of engines launched that use a wide range of fuels.

3. 2. New Engine Characteristics (Table 1)

(1) GM Duramax 3.0 L I-6 LZ0 (Fig. 5)

The LZ0 engine is the second-generation of its series and the successor model to the LM2. Power was increased by 10% and torque by 7.6%. It features refinements to several of its main components, including a revised combustion chamber shape and steel pistons, an optimized turbocharger compressor, new fuel injectors, and an improved temperature control function.

(2) Scania DC13 (Fig. 6)

This engine was launched in November 2021. It is the new 13-liter common base engine (CBE) for the Traton Group. Featuring a completely redesigned structure, the DC13 realizes an industry-leading 50% thermal efficiency. The Scania twin SCR system adopts dual injection of AdBlue® in the aftertreatment process, realizing excellent emissions treatment performance and complying with Euro VI. Maximum torque of 2,800 Nm is generated at 900 rpm, and fuel efficiency was improved by reducing the engine speed and seamlessly pairing the power band with the powertrain. This engine also features a newly designed DOHC-equipped integrated cylinder head as well as newly designed intake and exhaust ports, helping

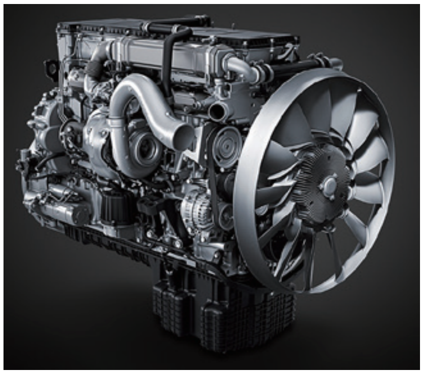

Fig. 7 Mercedes-Benz OM471

Fig. 8 FPT Industrial XCursor 13

to realize excellent intake and exhaust efficiency. Hydrotreated vegetable oil (HVO) can be used across the entire performance range of this engine series, and fatty acid methyl ester (FAME) biodiesel provides fuel flexibility for the 338 and 368 kW output engines.

(3) Mercedes-Benz OM471 (Fig 7).

The third-generation OM471 realizes improved combustion via refined combustion chambers and injection nozzles. The compression ratio was raised from 18.3 to 20.3, and the peak firing pressure was set to 25 MPa. Two types of new turbochargers are available, one emphasizing fuel economy that is manufactured in-house and one emphasizing high power. With the former fuel-efficient turbocharger, this engine reduces fuel consumption in the low and medium horsepower ranges by up to 4% compared with the previous model. Similarly, the high-power turbocharger reduces fuel consumption in the high horsepower ranges by up to 3.5%. This engine also features a newly developed oil pressure control valve that helps to raise fuel efficiency when combined with map controls using electric actuators and a newly developed low-viscosity engine oil. The aftertreatment system restricts exhaust pressure and heightens the uniformity of AdBlue® injection, thereby improving the NOx conversion efficiency and lowering fuel consumption. The adoption of closed loop control using NOx sensors and a predictive SCR temperature model helps to realize further stable improvements in emissions treatment performance and achieves compliance with Euro VIe.

(4) FPT Industrial XCursor 13 (Fig. 8)

The new XC13 realizes class-leading performance by improving combustion efficiency and makes a major contribution to efforts to comply with Europe's 2025 CO_2 emissions targets. This engine features a cylinder head and block manufactured from compacted graphite iron (CGI), and is 10% lighter than the previous generation. Combustion efficiency was raised by increasing the peak firing pressure to 27 MPa (30% higher than the previous generation) and the fuel injection pressure to 250 MPa (13% higher). It is also equipped with a new and uniquely designed divided-flow turbocharger. In addition, FPT's proprietary software and low friction loss engine parts function to enhance both power and environmental performance, enabling compliance with Euro VIe. This is also FPT's first multi-fuel single base engine. The lineup features both diesel and gasoline engines, and a hydrogen version is also planned for the future.

(5) Cummins X10 (Fig. 9)

Cummins announced plans to launch its next-generation X10 10-liter diesel engine in North America in 2026. This engine was designed to replace both the current 9-liter class L9 and 12-liter class X12, and will comply with the U.S. EPA's 2027 regulations a year early. The engine is reported to lower NOx emissions by 75% while also improving fuel efficiency.

To comply with increasingly stringent emissions regulations, the X10 adopts a new aftertreatment system called the Heavy-Duty Compact Cross (HDCC) modular system that incorporates dual SCR and twin dosing. It also adopts a belt-driven high-power 48 V alternator and heater solutions for the aftertreatment system. Substantial improvements in combustion and thermal efficiency are realized by adopting the DOHC structure that has become common for heavy-duty commercial vehicle engines. The adoption of the advanced ultrahigh pressure XPI fuel injection system and an electronically controlled waste gate turbocharger is also reported to enable substantial reductions in fuel consumption. The common base structure of this engine comprises a so-called fuel-agnostic engine platform that can be powered by low-

Fig. 9 Cummins X10

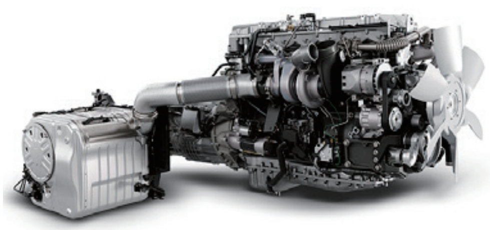

Fig. 10 Navistar International® S13

carbon natural gas fuels, hydrogen, and HVO. Virtually every component below the cylinder head gasket has been commonized, enabling various fuels to be adopted simply by customizing the parts above the gasket.

(6) Navistar International® S13 (Fig. 10)

The International® S13 was jointly developed with the Traton Group by a concurrent and integrated process that included the engine, transmission, and aftertreatment system. This enables up to 15% better fuel efficiency than the previous generation A26 engine depending on the aerodynamic package and other vehicle specifications. A higher combustion efficiency is achieved by the adoption of new combustion chambers, a compression ratio of 23, and a peak firing pressure of 25 MPa. It was reported that the adoption of a DOHC-compatible cylinder head will also enable further valvetrain and intake and exhaust efficiency improvements in the future. This engine adopts a dual SCR aftertreatment system to enhance NOx purification performance. SCR was selected as the main NOx conversion technology. By removing cooled EGR from the combustion cycle under normal operating conditions, it was possible to adopt a simple and highly reliable fixed-geometry turbocharger. In addition, since the engine generates little soot or particulate matter, there is no need for active DPF regeneration or the installation of a diesel oxidation catalyst (DOC) in the aftertreatment system.

4 Research and Development Trends

Automakers around the world are accelerating efforts toward the same goal of decarbonization. According to the framework issued by the International Organization of Motor Vehicle Manufacturers (OICA), the creation of a practical and sustainable roadmap in every country to achieve carbon neutrality by 2050 will require the adoption of technologies that suit the situation in those countries and the application of flexible policy measures. Consequently, it has adopted a technology-neutral approach to the relevant issues. To realize carbon neutrality, it will be necessary to reduce CO_2 emissions from vehicles currently on the road as well as new vehicles. This requires the development of both ZEVs that produce zero direct CO_2 emissions and internal combustion engines powered by energy sources that offset CO_2 emissions (i.e., carbon-neutral fuels). Therefore, a wide range of technological advances will be important, and further reductions in the greenhouse gas (GHG) emissions and fuel consumption of diesel engines will be necessary. Increasingly stringent emissions regulations are planned, as typified by the recently proposed Euro 7 standards. In addition to more stringent criteria, these regulations require manufacturers to guarantee the environmental friendliness of engines under all driving conditions, as well as under a wide range of environments and loads, and the initial environmental performance of engines must be maintained for longer periods of time. At the same time, lower engine fuel consumption and the combined use of hybrid technology are also bringing down overall exhaust temperatures, which may result in a deterioration in the performance of emissions aftertreatment systems in the future.

To satisfy more stringent regulations despite these lower exhaust temperatures, emissions measures will have to supplement longstanding approaches such as improving the performance of the catalyst itself and increasing the density of carrier cells with approaches to raise emissions treatment performance under on-road conditions, significantly lower ambient temperatures, and lower exhaust temperatures. For this reason, the research and development of thermal management systems is working to rapidly increase and maintain catalyst temperatures at ranges that realize high emissions treatment performance. Other approaches have been suggested, such as introducing two-stage SCR catalysts and urea injection, raising the engine exhaust heat amount, and lowering the thermal capacity of the exhaust system, as well as installing and securing sufficient power for coil heaters. At the same time, engine control technologies capable of accurately and robustly managing these systems will become more and more important.

Potential ideas for reducing GHGs and improving combustion include existing approaches for optimizing combustion, higher efficiency superchargers, higher pressure fuel injection systems that produce more finely atomized sprays, and the adoption of variable auxiliary devices to reduce cooling and mechanical losses. Development is also focusing on improving fuel efficiency via the overall powertrain, including creating optimal controls for combining engines with mild hybrid systems, optimizing engine torque curves, and reducing engine speeds in frequently used load ranges.

To achieve carbon neutrality in 2050 by reducing CO_2 emissions from road transport on a global basis, the results of studies carried out by the Japan Automobile Manufacturers Association (JAMA) found that scenarios featuring the rapid spread of battery electric vehicles (BEVs) must be accompanied by scenarios incorporating the active use of hybrid electric vehicles (HEVs), PHEVs, and carbon-neutral fuels as the best way to meet the climate change goals of the Intergovernmental Panel on Climate Change (IPCC). The reduction of polluting emissions, the improvement of fuel efficiency, and compatibility with a wide range of carbon-neutral fuels are some of the items that must continue to be addressed by diesel engine development in the future.

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