DIESEL ENGINES

1 Introduction

New fuel economy standards for passenger and other vehicles mandating a 32.4% fuel efficiency improvement over actual 2016 values by 2030 have been established in Japan. Diesel heavy-duty vehicle gradually began to comply with the 2016 emissions regulations in that year, and all new vehicles with a gross vehicle weight exceeding 3.5 t have been compliant with those regulations since 2019. Similarly, for heavy-duty vehicles, new fuel economy standards aiming to strengthen the original 2015 standards by 13.4% for trucks and 14.3% for buses by 2025 have been set.

In Europe, real driving emissions (RDE) regulations applying to emissions from passenger and other vehicles have been in effect since 2017. The NOx standard value in the RDE regulations was set to a maximum of 2.1 times the bench test regulatory value until 2019 (Euro 6d-TEMP). However, since 2020, a maximum of 1.5 times has come into effect (Euro 6d). At the same time, CO_2 emissions reduction for new vehicles in 2020 and later have been set (in comparison to 2021, a reduction of 15% in 2025 for passenger vehicles and vans, and reductions of 37.5% and 31%, respectively, in 2030). For heavy-duty vehicles, Euro VI-D came into effect in 2018, imposing stricter requirements on real driving emissions tests. Targets for heavy-duty vehicle CO_2 emissions reduction (a 15% reduction by 2025, and a 30% reduction by 2030 compared to 2019 levels) have also been determined.

In the U.S., the California Air Resources Board (CARB) is considering a significant tightening of NOx regulations for heavy-duty vehicles in 2024 and 2027. Coordinating with the Environmental Protection Agency (EPA) to set a nationwide standard as of 2027 is also being examined. Regulations on greenhouse gases (GHGs) will enter Phase II in 2021, representing a gradual strengthening of regulation values.

2 Trends in Japan

2. 1. Overview

(1) Diesel Engines for Passenger Vehicles

Mitsubishi Motors launched the 4N14, an engine with a 2.2-liter displacement designed for SUVs. European manufacturers have also been expanding the introduction of their diesel vehicles in the Japanese market.

(2) Diesel Engines for Commercial Vehicles

The GH8 engine for heavy-duty trucks, featuring a 7.7-liter displacement, was introduced by UD Trucks. Adaptations to make diesel heavy-duty vehicles compliant with the 2016 emissions regulations were completed.

2. 2. New Engine Characteristics (Table 1)

(1) Mitsubishi Motors 4N14 (Fig. 1)

The system designed for compliance with the European Euro 6d-TEMP regulations was used as is to develop this engine for the Japanese market. The achieved by reducing the moment of inertia in the piston-crankshaft system, decreasing slide resistance, and adopting a variable hydraulic relief mechanism The aftertreatment system uses urea SCR.

(2) UD Trucks GH8 (Fig. 2)

This is a 7.7-liter engine shared with the Volvo Group. Both emissions and fuel economy were calibrated for the

Fig. 1 Mitsubishi Motors 4N14

Table 1 Specifications of engines announced and launched in Japan in 2019

Region	Application	Manufacturer	Engine type	Cylinder arrangement	Bore diameter × stroke (mm)	Total displacement (cc)	Compression ratio	Maximum power (kW/rpm)	Maximum torque (Nm/rpm)	Characteristics
Japan	Passenger vehicles	Mitsubishi	4 N14	L4	86 × 97.6	2,267	14.4	107/3,500	380/2,000	Common rail, VG turbocharger, lower inertia weight in the piston-crankshaft system and reduced slide resistance, variable hydraulic relief mechanism, urea SCR.
Japan	Commercial vehicles	UD Truck	GH8	L6	110 × 135	7.7	17.5	263/2,200	1,428/1,200−1,600	Common rail (2,000 bar), VG turbocharger, stepped combustion chamber, crankcase ventilation internal valve cover, air-fuel ratio sensor, exhaust pressure feedback controlled shutter.
Outside Japan	Passenger vehicles	Mercedes-Benz	OM654 q	L4	82 × 92.3	1,950	15.5	85/3,400−4,400 110/3,400−4,400 140/3,800	280/1,200−2,600 320/1,400−3,200 400/1,600−2,600	DOHC, aluminum cylinder block, steel pistons, common rail (2,050 bar), VG turbocharger, engine-mounted high- and low-pressure loop EGR, DOC, SDPF, and SCR, SCR and ASC mounted under the vehicle body.
Outside Japan	Passenger vehicles	Volkswagen	EA288 2.0 TDI Evo	L4	81.0 × 95.5	1,968	16.2	110/3,000 to 4,200 (7-speed DSG T/M) 110/3,250 to 4,200 (6-speed T/M)	360/1,600−2,750 340/1,600−3,000	DOHC, smaller main crankshaft and connecting rod bearing diameter, steel pistons, cylinder heads and cylinder blocks cooled by separate systems, electric coolant pump, SCR catalysts and urea injectors mounted both in the engine and under the vehicle body.
Outside Japan	Passenger vehicles	GM	Duramax 3.0 L	L6	84 × 90	2,993	15.0	204/3,750	624/1,500	DOHC, aluminum cylinder block, steel cylinder liner, cast iron crankshaft and connecting rod, aluminum alloy pistons, common rail (2,500 bar), water-cooled VG turbocharger, water-cooled intercooler, high- and low-pressure loop EGR, electronically-controlled variable intake manifold, variable discharge oil pump.
Outside Japan	Passenger vehicles	FCA	3.0 L EcoDiesel V6	V6	83 × 92	2,988	16.0	194/3,600	651/1,600	DOHC, newly designed intake port, aluminum cylinder block, aluminum alloy pistons, common rail (maximum injection pressure of 2,000 bar), water-cooled VG turbocharger, high- and low-pressure loop EGR.
Outside Japan	Commercial vehicles	MAN	D15	L6	115 × 145	9,037	21.0	243/1,800 265/1,800 294/1,800	1,600/1,000−1,400 1,700/1,000−1,400 1,800/1,000−1,500	Maximum combustion pressure of 230 bar, common rail (2,500 bar), no cooled EGR, refined urea SCR, continuously regenerating trap (CRT) DPF, exhaust temperature control via an intake/exhaust throttle valve, continuously adjustable variable water pump.
Outside Japan	Commercial vehicles	Volvo Trucks North America	D13 TC	L6	131 × 158	12.8	18.0	302/1,500−1,950 317/1,600−1,900 339/1,600−1,900	2,372/1,300−1,500 2,372/1,300−1,500 2,521/1,200−1,500	Dynamic Torque system that automatically adjusts torque in accordance with vehicle weight, as well as road gradient and conditions, refined wave pistons, compression ratio increased from 17 to 18.
Outside Japan	Commercial vehicles	Scania	DC13 166	L6	130 × 160	12.7	21.0	397/1,800	2,700/1,000−1,300	No cooled EGR, ball bearing turbocharger, DPF and urea SCR.

Fig. 2 UD Truck GH8

Japanese market, making it compliant with the 2016 emissions regulations as well as exceeding the heavy-duty vehicle fuel economy standards by 5% in all models. All vehicle models that have adopted this engine use a 12-speed electronically-controlled automatic transmission (ESCOT-VI), achieving drivability comparable to that of vehicles equipped with an 11-liter engine. The downsizing of the engine has also reduced the weight of the chassis of trucks using it by approximately 320 kg.

3 Trends outside Japan

3. 1. Overview

(1) Diesel Engines for Passenger Vehicles

In Europe, adapting to Euro 6d-TEMP has wound down, and engines compliant with Euro 6, which comes into effect in 2020, are being introduced into the market. Mercedes-Benz has launched the OM654q Euro 6d compliant 2-liter engine, while Volkswagen has released the

2-liter EA288 2.0 TDI Evo, which also complies with Euro 6d. To conform with the stricter NOx standard values in the RDE regulations, these engines rely on mounting an SCR catalyst under the engine and vehicle body. Meanwhile, in the U.S., the GM 3-liter inline 6-cylinder Duramax and the Fiat Chrysler Automobiles (FCA) 3-liter V6 EcoDiesel engines have been released. These engines for full-size pickup trucks aspire to provide high power and high torque, as well a low fuel consumption.

(2) Diesel Engines for Commercial Vehicles

The 9-liter D15, a downsized version of the original 10.5-liter D20, was released for heavy-duty trucks by MAN. Volvo Trucks North America launched a refined version of its 13-liter D13TC turbo compound engine that features improved fuel efficiency. Scania introduced the DC13 166, which increases the power of the 13-liter DC13 to 397 kW.

3. 2. New Engine Characteristics (Table 1)

(1) Mercedes-Benz OM654q (Figs. 3 and 4)

The use of technologies such as installing high- and low-pressure EGR, a DOC, an SCR-catalyzed DPF (SDPF) and SCR in the engine, and mounting the SCR and ammonia slip catalyst (ASC) under the vehicle achieved compliance not just with Euro 6d-TEMP, but also with the Euro 6d regulations coming in effect in 2020.

(2) Volkswagen EA288 2.0 TDI Evo (Fig. 5)

Using the new twin dosing system that injects urea upstream of two SCR catalysts arranged inline to achieve compliance not just with Euro 6d-TEMP, but also with the Euro 6d regulations coming in effect in 2020. The first SCR catalyst is mounted in the engine, and the second one is installed under the vehicle body. The first catalyst is close to the engine and therefore quickly raises the temperature of the catalyst even in cold starts to achieve a high NOx conversion efficiency while the temperature of the second SCR catalyst drops by 100℃ due to being away from the engine, providing highly efficient NOx conversion even at the high exhaust temperatures of 500℃ near the engine.

(3) GM Duramax 3.0-Liter (Fig. 6)

This inline 6-cylinder engine aims for top-class high power, high-torque, and fuel efficiency and features an aluminum deep-skirt cylinder block, reducing its weight

Fig. 3 Mercedes-Benz OM654q

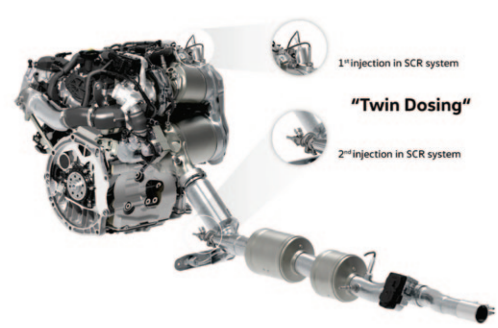

Fig. 5 Volkswagen EA288 2.0 TDI Evo

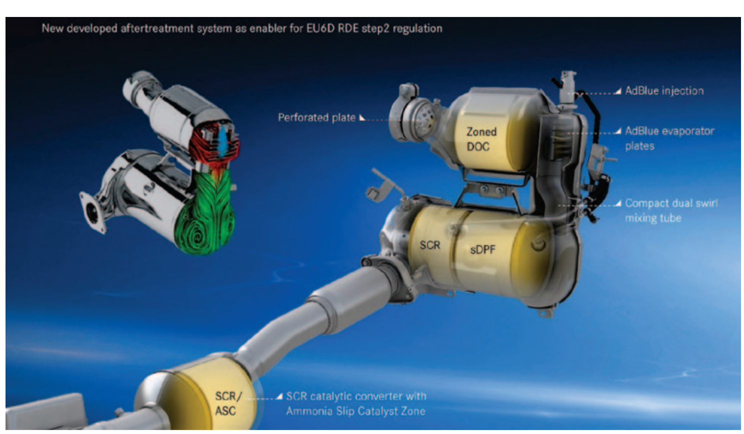

Fig. 4 Mercedes-Benz OM654q Aftertreatment System

Fig. 6 GM Duramax 3.0-Liter

Fig. 7 FCA 3.0-Liter EcoDiesel V6

Fig. 8 MAN D15

by 25% compared to a cast iron block, while using iron for the cylinder liner to ensure durability. Forged steel is used for the crankshaft and connecting rod. Turbocharging reaches a maximum boost pressure of 300 kPa through the adoption of a water-cooled VG turbocharger (ball bearing) and a water-cooled intercooler. It also has both high- and low-pressure loop EGR. In addition, air flow is optimized for the engine speed by a variable intake manifold using electronically-controlled flap valves to switch between two intake passages of different lengths in each cylinder. The engine also features technologies such as a variable displacement vane oil pump.

(4) FCA 3.0-Liter EcoDiesel V6 (Fig. 7)

This engine, known as the third-generation 3.0-liter EcoDiesel V6, increases torque by 14% and power by 8% compared to its predecessor. The intake port swirl and coefficient of flow of the cylinder heads have been improved. The cylinder block is made of CGI cast iron, while the crankshaft and connecting rod are made of forged steel. The engine features a water-cooled VG turbocharger, high- and low-pressure loop EGR and a newly designed combustion chamber that reduces the compression ratio from 16.5 to 16.0.

(5) MAN D15 (Fig. 8)

The D15 has a maximum combustion pressure of 230 bar. Cooled EGR has been eliminated, and an improved urea SCR and continuously regenerating trap (CRT) DPF have been introduced. Engineering that promotes the warm-up process and maintains a high exhaust temperature, a coolant pump with a continuously adjustable rotational speed and various other technologies have been used to optimize the engine and auxiliary thermal management and achieve a high efficiency. In addition, the unique MAN Turbo-EVBec engine brake system delivers a maximum of 340 kW of engine brake power. Downsizing to the D15 from its D20 predecessor gives trucks an extra 230 kg of carrying capacity.

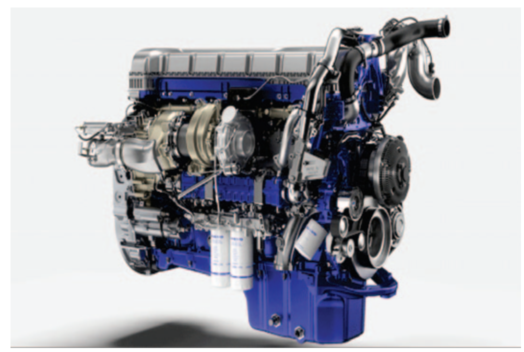

Fig. 9 Volvo D13TC

(6) Volvo Trucks D13TC (Fig. 9)

Volvo Trucks North America has refined the fuel consumption performance of the turbo compound engine it introduced to the North American market in 2017, and announced plans to start production at the end of the 2020 fourth quarter. It offers a selection of three drive modes (Extra Efficiency, Economy, and Performance) and the Dynamic Torque system that automatically adjusts the torque in accordance with the vehicle weight, as well as the road gradient and conditions. The air-fuel mixture in the cylinder has a more even distribution, and refined wave pistons provide reliable combustion. The compression ratio has been increased from 17 to 18. The new turbo compound engine improves reduces fuel consumption by 3% compared to the original D13TC, resulting in a reported overall reduction of up to 11% compared to 2015 truck models.

(7) Scania DC13 166 (Fig. 10)

Offering a maximum power of 397 kW, this engine sets expectations of greater drivability and power than the

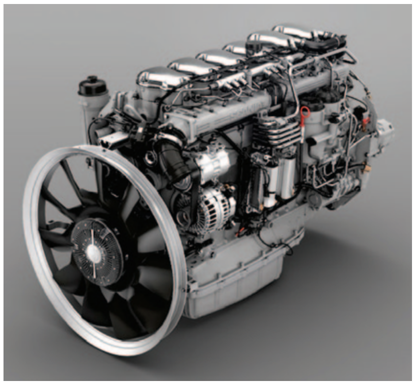

Fig. 10 Scania DC13

382 kW of the higher rank V8 16-liter DC16, and was developed to address the issues of vehicle weight and front axle weight prone to arise in vehicles equipped with a V8 engine. It reportedly provides the benefit of a 2% reduction in fuel consumption. Its specifications, such as the use of a ball bearing turbocharger, are essentially the same as those already set for the 368 kW engine.

4 Research and Development Trends

In Europe, the concentration NOx, PM 2.5, and other air pollutants continues to exceed the air quality standard targets set by European governments and the World Health Organization (WHO). The already noted introduction and strengthening of RDE regulations covering real-world driving aim to remedy this situation. Japan will also apply RDE regulations to diesel passenger and other vehicles starting in 2022. In the U.S., the State of California is looking into strengthening the emissions regulatory values for heavy-duty vehicles and introducing the Low Load Cycle test. Establishing a unified standard with the Environmental Protection Agency (EPA) is also under consideration. Lower engine fuel consumption, and the combined use of hybrid technology are also bringing down overall exhaust temperatures.

A significant improvement of urea SCR NOx conversion efficiency over a wider range of low to high temperatures will be required to comply with such stricter regulations and lower exhaust temperatures. Research and development on the relevant technologies is ongoing. In addition to maintaining the longstanding approaches such as improving the performance of the catalyst itself and increasing the density of carrier cells, that research and development is expected to further focus on new approaches. Examples include urea injection optimizations such as the use of multiple SCR catalysts, their location, and the use of two injectors, as well as technology to maintain the temperature of the exhaust pipes and canning holding the catalyst, and engine control technology that raises and maintains the temperature of the catalyst early. Suppressing the increase in back pressure that accompanies the higher number of catalysts will also be a critical issue in achieving balance with lower fuel consumption.

At the same time, there is increasing demand to reduce CO_2 and other greenhouse gases in response to global warming.

The need to reduce CO_2 has prompted the development engines and powertrains that decrease fuel consumption through engine downsizing, torque curve optimization, and lower engine speed in the operating range. Similarly, fuel-efficient technologies such as greater cycle efficiency stemming from raising combustion and turbocharger efficiency, the reduction of cooling, exhaust, and friction losses, improved aftertreatment performance and optimized aftertreatment control seek to address that need. Further advances in these technologies, as well as the development of new fuel-efficient technologies, will become increasingly important.

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