Next-generation boxer diesel

Subaru's latest boxer diesel engine meets Euro 5 emissions regulations without compromising power output, fuel economy or NVH performance

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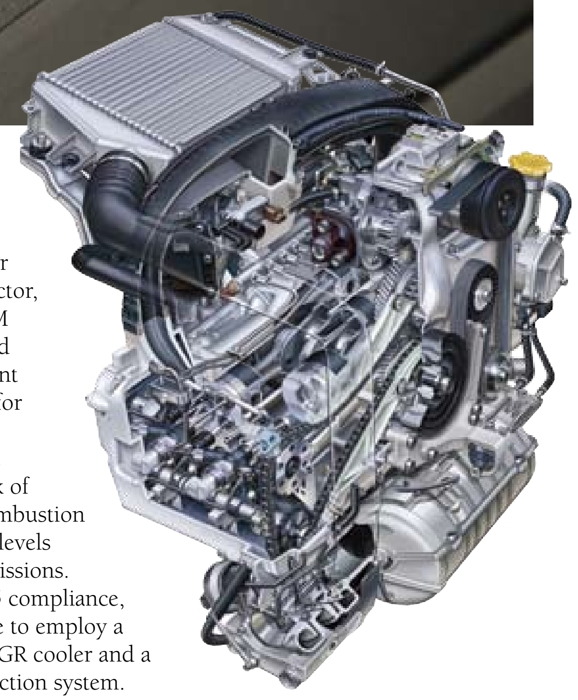
In recent years, being environmentally friendly has become an important feature for new passenger cars. Diesel cars, which produce lower CO_2 emissions, dominate new car sales in Europe, taking a 50% share of the market. It was for this reason that in 2008, Subaru launched the Euro 4-compliant boxer diesel Legacy. Employing a common-rail system and a variable nozzle-type turbocharger, the Subaru boxer diesel offers output performance and fuel economy that are well suited to an AWD vehicle platform.

The 2008 boxer diesel won praise from consumers, the media and the industry alike. However, the development concept of the second-generation boxer diesel was to satisfy Euro 5 regulations while maintaining the engine output performance, fuel economy, and NVH characteristics of the Euro 4-compliant boxer diesel.

For Euro 5, the NOx and PM elements must be reduced by at least 30% and 80% respectively from the Euro 4 levels. To realize this, the development team reduced PM by improving the DPF that is employed in the

New Legacy has been launched with the second-generation diesel boxer – an engine that offers excellent NVH behavior, engine performance and fuel economy

Compliant with Euro 5 legislation, the all-new boxer diesel engine (below) has been launched in the new Legacy (left)



Forester and Impreza models, and reduced NOx by developing advanced combustion control.

Engine configuration

The main configuration of the new engine is based on the conventional boxer diesel. The benefit of the boxer engine is that it enables a compact, lightweight and highly rigid design compared with an inline four-cylinder unit. It also offers excellent NVH behavior, engine performance, and fuel economy.

To extend the stroke, but keep the overall width of the engine equivalent to that of a four-cylinder boxer petrol engine, the boxer diesel employs a diagonally split connecting rod and a different method of assembly. This has minimized the increase in the cylinder block deck height. Furthermore, the piston height is kept compact by employing high-strength aluminum alloy pistons. The cylinder head comprises four valves and center injection. Employing proprietary fuel spray injectors with short overall length, the cylinder-head height is lower than in the boxer petrol, successfully maintaining the engine overall width equivalent to that of the petrol.

> **"In total, the boxer diesel achieved a weight reduction of 10kg compared with a typical 2-liter four-cylinder diesel powertrain"**

In general, diesel engines are much heavier than their petrol counterparts. To minimize the increase in weight, the overall length of the boxer diesel engine is shorter than that of the boxer petrol. The bore pitch was shortened by 14.6mm compared with the boxer petrol, giving an overall length of 353.5mm, which is 61.3mm shorter than the boxer petrol. In total, the boxer diesel achieved a weight reduction of 10kg compared with a typical 2-liter four-cylinder diesel powertrain, through the compactness of short overall length and width, combined with the balancer shaft-less structure coming from the good noise and vibration characteristics and the weight reduction of various parts.

The turbocharger is of a variable nozzle type, which controls the vane opening around the exhaust turbine according to the operating range, giving highly efficient supercharging in all ranges. The turbocharger is located under the engine to ensure good exhaust gas conversion and give a low center of gravity. The characteristic dynamic performance of the Subaru is realized through the lowered center of gravity and enhanced supercharging response.

The oxidation catalyst and the DPF are located directly downstream of the turbocharger. This layout enables the catalyst to warm up more quickly, securing the exhaust gas conversion performance in a wide operating range.

Aftertreatment system

The aftertreatment system for the Euro 5-compliant boxer diesel incorporates several new features. The DPF system located directly downstream of the turbocharger, equipped as standard in the first-generation boxer diesel for the Forester, has improved PM converting capability. For emissions conversion, especially the NOx, five features have been adopted: large EGR cooler; new fuel injection system; new combustion chamber shape; low compression ratio; and lift sensors for variable nozzle-type turbocharger actuators.

The major difference in the regulations between Euro 4 and Euro 5 is in the permissible emission levels of PM and NOx. The improvement of air utilization factor is effective for the reduction of PM emissions, and the decrease of combustion temperature is effective for the reduction of NOx emissions. To restate: the two keywords for PM and NOx reduction are combustion temperature and air utilization factor. In general, when a large volume of EGR gas is introduced into the combustion chamber with a large-sized EGR cooler, the low temperature levels of the EGR gas helps to reduce NOx emissions. However, the decreased combustion rate often impairs the thermal efficiency and leads to poor fuel economy. Moreover, the increased EGR rate lowers the air utilization factor in the cylinders and increases PM emissions. A large-sized EGR cooler is good for NOx reduction, but could worsen fuel economy and raise PM.

Furthermore, the new fuel injection system has an increased fuel pressure at normal range, with eight holes that are 9% smaller in diameter than those of the previous system. This promotes the atomization of fuel spray and the increase of air utilization factor, leading to PM reduction and quick, efficient combustion for better fuel economy. Yet there is a risk of increased combustion temperature levels and NOx emissions.

For Euro 5 compliance, Subaru chose to employ a large-sized EGR cooler and a new fuel injection system. Engineers also set out to develop a combustion chamber shape that maximizes the benefits of the large-sized EGR and the new fuel injection.

The shape of the combustion chamber is an important factor, because it is where the atomized fuel meets oxygen to cause combustion. The development team used CAE analysis of space and time to investigate the combustion of the fuel injected into the chamber.

In the Euro 5 system, where the diameters of the chamber lip and the chamber cavity are extended and the cone angle is optimized, it is clear that the PM generation in the cavity is reduced. In addition, the high PM consistency area at 26° ATDC (after top dead center) has been considerably reduced compared with the Euro 4 system. This is the result of PM oxidation, which has been promoted by the improvement of air utilization factor.

The intake airflow is another important factor for controlling fuel diffusion in the combustion chamber and the combustion rate. The air is taken in through a helical port and a tangential port to create a swirl inside the combustion chamber and to diffuse the fuel so that oxygen and fuel are mixed. The optimum velocity and streamline are where the neighboring fuel

	Euro 5 Boxer Diesel	Euro 4 Boxer Diesel
Cylinder Configuration	Horizontally-Opposed 4-cylinder	Horizontally-Opposed 4-cylinder
Displacement (cc)	1,998	1,998
Bore x Stroke (mm)	86.0 × 86.0	86.0 × 86.0
Compression Ratio	16.0	16.3
Valve Train	DOHC 4 valves	DOHC 4 valves
Fuel Injection System	Common Rail (Latest generation)	Common Rail
Maximum Power (kW (PS)/rpm)	110 (150) /3,600	110 (150) /3,600
Maximum Torque (Nm (kgfm)/rpm)	350 (35.7) /1,800 – 2,400	350 (35.7) /1,800

Table 1: Comparing the technical features of the two boxer diesel powertrains

	Euro 5 Boxer Diesel	Euro 4 Boxer Diesel
Type	Solenoid (Latest generation)	Solenoid
Max. Injection Pressure (MPa)	180	180
Number of Holes	8	8
Hole Diameter(mm)	0.121	0.133

Table 2: Further important differences between the two boxer diesel powertrains

ITEM	Results for EURO5
NOX	Lower(Better) than EURO4 Forester & Impreza ↘
PM	Same as EURO4 Forester & Impreza ⇨

Combustion Factor		Conditions	Hardware Component	NOx	PM
1	Injection Timing	Retard ↘	2) New Fuel Injection System	↘	↘
2	Fuel Pressure	Higher ↗	2) New Fuel Injection System	⇨	↘
3	EGR Rates	Heavier ↗	1) Large Size EGR Cooler 5) Lift Sensor For VNT	↘	↗
4	Intake Pressure	Higher ↗	5) Lift Sensor For VNT	⇨	↘
5	Ignition Delay	Shorter ↘	2) New Fuel Injection System 3) New Combustion Chamber	↘	⇨
6	Combustion Speed	Faster ↗	2) New Fuel Injection System 3) New Combustion Chamber	↗	↘
7	Combustion Temperature	Lower ↘	4) Low Compression Ratio 1) Large Size EGR Cooler	↘	↗

Table 3: The degree of influence of each combustion factor for NOx and PM emissions

sprays are not made to overlap each other by the swirl. The engineering team also focused on the lowered compression ratio, which is aimed at decreasing the combustion temperature to reduce NOx. The combustion temperature has been decreased by about 100°C. As well as satisfying the Euro 5 NOx limit, the influence of the low compression ratio on theoretical thermal efficiency and on PM emissions has been minimized.

The development team concluded that the best compression ratio for the Euro 5 system is 16.0, compared with 16.3 in the Euro 4 system.

The final feature to be introduced is the lift sensors for the variable nozzle-type turbocharger actuator. The lift sensors help to keep the boost pressure high at low load range, thereby raising the oxygen concentration in the combustion chamber and improving the air utilization factor. This leads to a reduction in PM emissions.

To maximize the effects of these five new hardware items, the development team conducted a series of elaborate and highly accurate calibration tests. The engine control strategy is made up of a complicated matrix structure compared with the Euro 4 system. The influence on the combustion varies according to combinations of parameters such as the pressure, timing, the number and the time period of fuel injections. In addition, by optimizing the EGR rate control and boost pressure control at all operating ranges, the best performances of engine output, fuel economy, and emissions conversion have been achieved.

Figure 1 illustrates a graph that compares cylinder pressure, rate of heat release and cylinder temperature levels for the Euro 5 and Euro 4 systems. The operating conditions are third gear, 1,600rpm, which is equivalent to 25mph vehicle speed, and mid-level load of 750kPa indicated mean effective pressure (IMEP).

In the Euro 5 system, as more EGR gas is introduced and the combustion rate is controlled at a much faster level compared with the Euro 4 system, the overall thermal efficiency level is vastly improved, and as a result of this, the combustion temperature level is maintained at about 100°C lower.

The second-generation boxer diesel boasts several new features including a new DPF system (right)

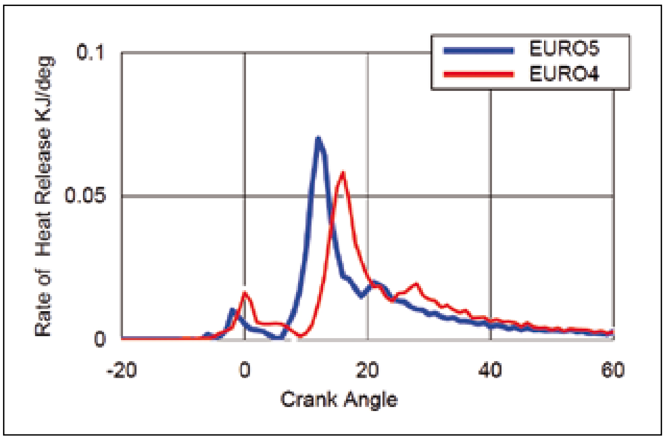


Figure 1 compares the rate of heat release of the two boxer diesel powertrains

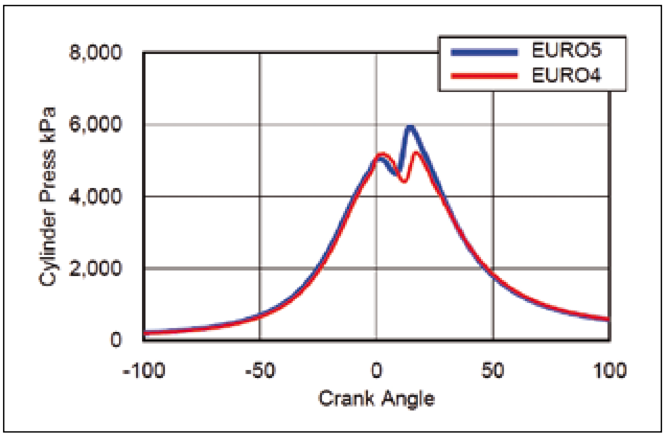


Figure 2 compares the cylinder pressure levels of the two boxer diesel powertrains

Table 3 shows the degree of influence of each combustion factor for NOx and PM emissions respectively. The reduction of NOx and PM was realized by the combination of five hardware components and seven combustion factors. As can be seen, the influence of combustion factors on NOx and PM varies. By balancing these complex factors, the new engine cut NOx by about 60%.

NVH performance

The Euro 5 boxer diesel maintains the NVH standards of the Euro 4 system while also satisfying the Euro 5 regulation.

In general, the high combustion pressure of diesel engines leads to greater combustion noise and engine vibration. The boxer diesel reduced such NVH and maximized its potential for stillness, realizing smooth and lively driving with low noise and vibration in all ranges from idling to high speed, without the need for balance shafts. The combustion noise, which could have deteriorated by making it Euro 5 compliant, has been maintained at the same level as the Euro 4 system, after reviewing the number of multi-stage injections and calibration strategies for driving conditions.

The second-generation boxer diesel has been launched into the European market, satisfying the Euro 5 regulation while maintaining the engine output, fuel economy, and NVH and vibration characteristics of the first-generation engine.

The development of this engine had two outcomes. First, five new features have been introduced: a large-sized EGR cooler; a new fuel injection; a new combustion chamber shape; low compression ratio; and lift sensors for the actuators of variable nozzle-type turbocharger. These features, in combination with the DPF, enable the second-generation boxer diesel to meet Euro 5. The second outcome is that the quietness and fuel economy of the first-generation engine have been maintained. ETi