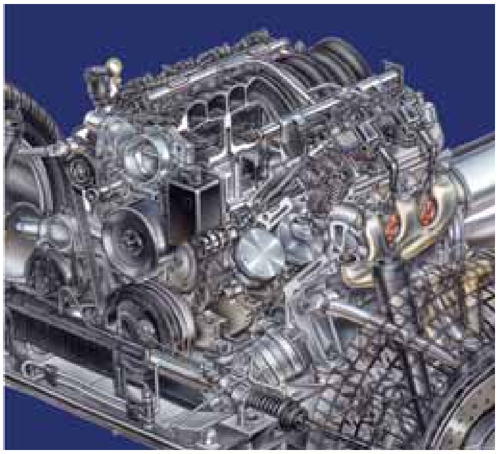
# Small Block goes big



*The 2005 LS2, the most powerful standard engine in Corvette history, gets a 0.3-L increase in displacement, a higher 10.9:1 compression ratio, and a redline bumped to 6500 rpm.*

The new 2005 **Chevrolet** C6 Corvette features the most powerful standard engine in Corvette history. The 6.0-L LS2 V8, part of the fourth generation of **General Motors**' Small Block engines, delivers 400 hp (298 kW) at 6000 rpm and 400 lb·ft (542 N·m) at 4400 rpm—increases of 50 hp (37 kW) and 40 lb·ft (54 N·m) over the previous Corvette's 5.7-L LS1. (The first Small Block in 1955 displaced 265 in$^3$ [4.3 L] and put out 195 gross hp.) The 0.3-L increase in displacement is the result of an increase in cylinder bore diameter to 101.6 mm (4.00 in); stroke is 92 mm (3.62 in). Compression ratio is raised from 10.1:1 to 10.9:1 and maximum engine speed is bumped from 6200 to 6500 rpm.

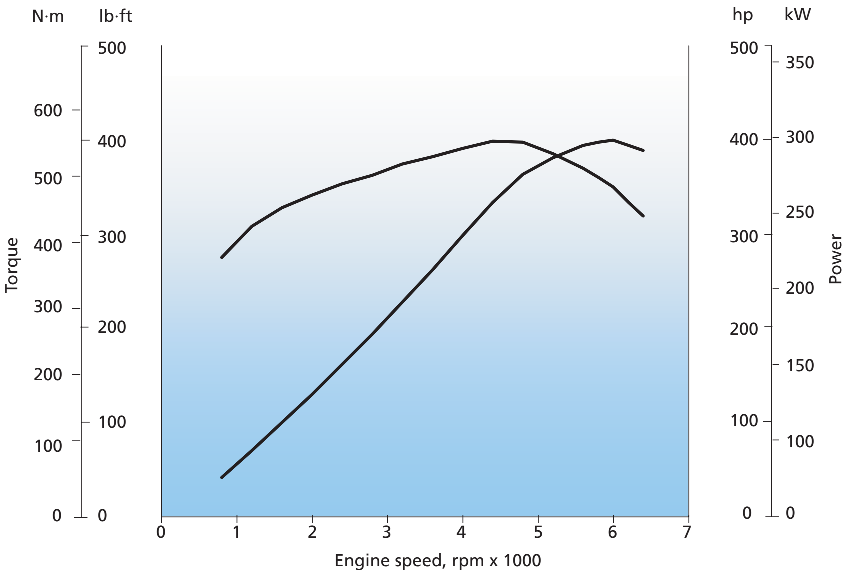
"More than dynamometer numbers, the LS2 engine's range of power and torque is broad and very usable in everyday driving," said Dave Muscaro, **GM Powertrain**'s Assistant Chief Engineer of car Small Blocks. "This engine is smoother, and more refined, but at the same time retains tire-thrashing output."

The LS2's "cam-in-block" Gen IV architecture is based on that of the LS1 5.7-L Gen III engine of the Corvette C5. Like all Small Blocks, the new engine features a 90° cylinder bank vee and 4.40-in (112-mm) bore centers. As with the Gen III, the latest engine has a lightweight block cast from aluminum (319-T5) with cast-in-place iron cylinder bore liners. Structural rigidity is enhanced by a deep-skirt engine block, which extends below the crankshaft centerline, and by two horizontal cross bolts for each main bearing cap, which complement the four traditional vertical main cap bolts.

Crankcase breathing and ventilation are improved using techniques employed on the C5 Z06's LS6 engine, including moving the crankcase ventilation system's PCV valve away from the rocker covers and into the block valley. A die-cast aluminum valley cover and upper deck rails link the cylinder banks for increased torsional and bending stiffness. Performance and efficiency benefit from a "balanced cylinder head design" with identical airflow and energy direction for each cylinder.

The LS2 incorporates several significant changes compared to the Gen III-based LS1 that help improve performance, reliability, and serviceability.

Its new aluminum block casting incorporates provisions for external knock sensors, which improve serviceability, and revised oil galleries. The LS2's new "wingless" oil pan with cast baffling reduces mass and provides better oil control under the extreme demands of high-rpm, high ***g***-force driving maneuvers. The switch from a "gull-wing" oil pan also reduces engine oil capacity from 6.5 to 5.5 qt (6.1 to 5.2 L) with a dry filter. The camshaft sensor is relocated from the rear



*The Corvette's new 6.0-L LS2 V8 delivers 400 hp (298 kW) at 6000 rpm and 400 lb·ft (542 N·m) at 4400 rpm—increases of 50 hp (37 kW) and 40 lb·ft (54 N·m) over the previous Corvette's 5.7-L LS1.*

to the front of the block to provide room for the new oil galleries. Camshaft lift and throttle body size are increased—the latter to 90 mm (3.54 in) for the single-blade design—to take advantage of increased cylinder head flow.

The cylinder heads are derived from those used on the LS6, including raised intake ports and an unshrouded valve combustion chamber design that, when combined with the engine's flat-top pistons, produces a more efficient swirl of the air/fuel mixture. This efficiency enables a higher (10.9:1) compression ratio, which increases efficiency and power. A flat-top piston with lower ring tension reduces friction, and floating piston wrist pins reduce NVH. The 2-in (51-mm) intake and 1.55-in (39-mm) exhaust valves get springs upgraded to withstand the engine's increased power and rpm range.

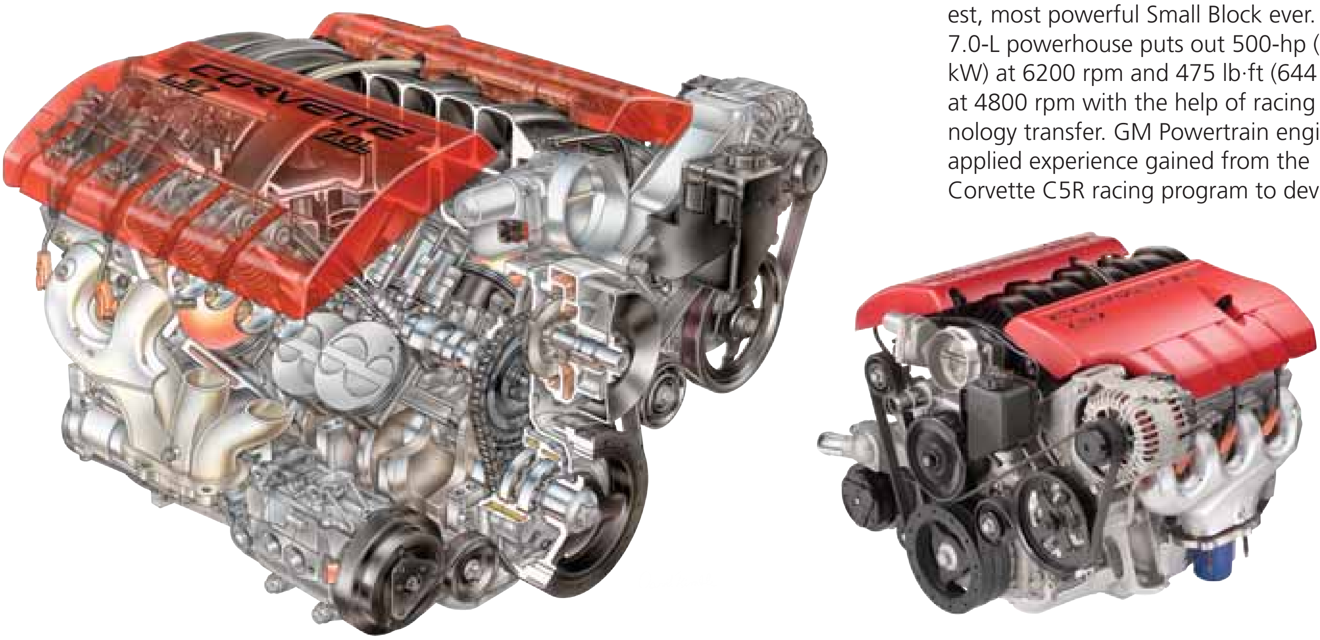
Engineers also increased the efficiency and reduced the mass of the exhaust manifolds. Airflow is enhanced by 4% and mass reduced by 33%, one of the major sources of the latter being a wall thickness reduction from 4 to 3 mm (0.16 to 0.12 in).

Advances in substrates allowed engineers to maintain the size of the catalytic converters while making them more effective and less restrictive. The new converters are mounted closer to the exhaust manifold for quicker lightoff and reduced cold-start emissions. So the more restrictive quad catalyst design of the LS1, with its small, auxiliary "pup" converters, was not necessary to meet emissions requirements. An additional benefit of exhaust system development was elimination of the LS1's air-injection-reaction system.

Other adjustments made to improve exhaust system performance included replacing sharp tubing angles with more gradual bends. A larger muffler volume and tri-flow technology eliminated unwanted noise, particularly between 1500 and 2400 rpm. The inline (vs. the LS1's transverse) muffler flows more efficiently.

The LS2's new engine controller incorporates electronic throttle control (ETC) commands, so the separate ETC module of the LS1 is eliminated. This allows faster communication between controller and throttle and reduces system mass and complexity. And emissions are slightly improved with the damping of unnecessary throttle movement.

Joining the LS2 in the Corvette lineup will be the new 2006 Z06's LS7, the largest, most powerful Small Block ever. The 7.0-L powerhouse puts out 500-hp (373 kW) at 6200 rpm and 475 lb·ft (644 N·m) at 4800 rpm with the help of racing technology transfer. GM Powertrain engineers applied experience gained from the Corvette C5R racing program to develop



*The 7.0-L LS7 for the 2006 Z06 produces 500 hp (373 kW) at 6200 rpm and 475 lb·ft (644 N·m) at 4800 rpm with the help of racing technology transfer.*

GM Powertrain engineers applied experience gained from the Corvette C5R racing program to develop the LS7.

Unique hydraulic rollers for the LS7 help to actuate the larger valves and provide more valve lift.

The LS7 cylinder heads are CNC-ported and have very large (by production-vehicle standards) intake and exhaust ports to speed airflow.

many LS7 components. "In many ways, the LS7 is a racing engine in a street car," said Muscaro.

The LS7 is identified by red engine covers and is based on the new Gen IV Small Block architecture. But unlike the relationship between the LS1 and the previous Z06 engine, the LS7 has a distinct engine block casting and reciprocating assembly than the base engine. Compared to the LS2, it has a different front cover, oil pan, exhaust manifolds, and cylinder heads. The unique block accommodates large-displacement cylinders, while other components make use of racing-derived lightweight components to help boost power and ultimate engine speed to 7000 rpm.

The LS7's block has larger—104.8-mm (4.125-in)—cylinder bores, the latter enabled by pressed-in cylinder sleeves. Six-bolt, doweled-in-place, CNC-machined, forged-steel main bearing caps offer the strength required for the LS7's output. (The smaller-displacement LS2 engine has cast-in cylinder sleeves and powder-metal main caps.)

Aluminum flat-top pistons deliver an 11.0:1 compression ratio and are connected to a forged-steel crankshaft with a 101.6-mm (4.00-in) stroke via titanium connecting rods of just 480 g (16.9 oz) each—almost 30% less than those in the LS2. Their light weight enhances high-rpm performance and range.

The engine's dry-sump oil system, with a high-capacity 8-qt (7.6-L) reservoir and high-efficiency air-to-oil cooler, is designed to ensure proper lubrication during high cornering loads. Oil circulates through the engine, to the oil pan, then back to the reservoir via a scavenge pump.

Like other Gen IV engines, the LS7 uses a composite, three-piece, friction-welded intake manifold, although its passages are tuned for greater airflow re-

**LS7 Specifications**

| | |
|---|---|
| Engine type | "Cam-in-block" 90° V8 |
| Block configuration | Cast aluminum with pressed-in cylinder sleeves and six-bolt, forged-steel main bearing caps |
| Bore x stroke | 104.8 x 101.6 mm (4.125 x 4.00 in) |
| Displacement | 7.0 L |
| Power | 500 hp (373 kW) @ 6200 rpm |
| Torque | 475 lb·ft (644 N·m) @ 4800 rpm |
| Redline | 7000 rpm |
| Crankshaft | Forged steel |
| Connecting rods | Forged titanium |
| Pistons | Cast aluminum |
| Compression ratio | 11.0:1 |
| Cylinder heads | CNC-ported aluminum; 70-$cm^3$ chamber volume |
| Valves: | |
| Intake | 56 mm (2.20 in), titanium |
| Exhaust | 41 mm (1.61 in), sodium-filled |
| Camshaft | Hydraulic roller, 15-mm (0.591-in) lift (intake and exhaust) |
| Rocker arms | 1.8:1, offset (intake only) |
| Air intake | Composite manifold with 90-mm (3.54-in) throttle body |
| Fuel | 91 octane (minimum) |

**Corvette Engine Comparison**

| Corvette model | Base | | Z06 | |
|---|---|---|---|---|
| Engine | 2004 LS1 | 2005 LS2 | 2004 LS6 | 2005 LS7 |
| Displacement | 5.7 L | 6.0 L | 5.7 L | 7.0 L |
| Power | 350 hp (261 kW) at 5200 rpm | 400 hp (298 kW) at 6000 rpm | 405 hp (302 kW) at 6000 rpm | 500 hp (373 kW) at 6200 rpm |
| Torque | 375 lb·ft (508 N·m) at 4000 rpm | 400 lb·ft (542 N·m) at 4400 rpm | 400 lb·ft (542 N·m) at 4800 rpm | 475 lb·ft (644 N·m) at 4800 rpm |

*The LS7's aluminum flat-top pistons are connected to a forged-steel crankshaft with titanium connecting rods.*

quirements. Housed in the manifold are 90-mm (3.54-in), single-bore throttle bodies and higher-capacity, 5-g/s (0.18-oz/s) fuel injectors.

The aluminum cylinder heads are CNC-ported on state-of-the-art five-axis milling machines to meet airflow demands that are 25% greater than LS2's. The engine has straight intake runners and very large (by production-vehicle standards) ports to speed airflow. The combustion chambers are fed by large—56-mm (2.2-in)—titanium intake valves that each have a mass 21 g (0.7 oz) less than the stainless-steel valves used in the LS2 despite having 22% more area. The sodium-filled exhaust valves are 41.0 vs. 39.4 mm (1.61 vs. 1.55 in) in the LS2. The valve seats are Siamesed to accommodate the large valve face diameters, and experience with the C5R results in valve angles of 12° vs. 15° (for the LS2) for enhanced airflow.

Unique hydraulic rollers actuate the larger valves, and based on C5R racing experience, the LS7's cam has a new profile to provide 0.066 in (1.7 mm) more lift—0.591 vs. 0.525 in (15.0 vs. 13.3 mm)—on both the intake and exhaust valve. Higher-performance (1.8:1 vs 1.7:1) roller rocker arms, which are offset on the intake side, and raised valve spring seats accommodate the high valve lift and large ports.

On the exhaust side, hydroformed steel exhaust headers are unique to the LS7. Individual header tubes meet at a special quad-outlet collector flange at the header outlet where they smoothly attach to the "wide-mouth" catalytic converter for reduced back pressure. Four rectangular sections of the flange smooth the exhaust flow out of the engine.

LS7s will be hand-assembled at GM's new Performance Build Center in Wixom, MI, using procedures—such as deck-plate boring and honing of the cylinders and crank line-boring of the block with the deck plates and side bolts installed—normally associated with race-engine building. The engines are pushed through about 15 subassembly stations. Team members are engine-build specialists selected from GM's experimental engine lab, and they complete about 30 LS7 engines per day.

*Kevin Jost*

# BMW builds better inline six

"Efficient dynamics" is the declared goal of the **BMW** Group's drivetrain development division. "This resolves the apparent conflict between reducing consumption and emissions on the one hand and enhancing performance and agility on the other," commented Professor Burkhard Göschel.

With that goal in mind, BMW undertook development of a new 3.0-L inline-six gasoline engine, the R6, that is said to be the most comprehensive engine project since the introduction of its first automobile. Rather than upgrade its existing I6 to state-of-the-art technical specifications, which would have resulted in an engine 14 kg (31 lb) heavier, BMW engineers decided to develop an entirely new engine, leaving only the inline arrangement of six cylinders unchanged.

The high-tech power unit has a composite magnesium/aluminum crankcase, BMW's Valvetronic infinitely variable valve timing that eliminates the throttle butterflies, and a number of other innovations such as the world premiere of the electric water pump. The R6 is said to distinctly surpass the final version of its predecessor in every aspect. BMW's medium-term corporate plans reveal that around half of all new BMW cars will be powered by the engine.

Peak output of the R6 surpasses its predecessor by 20 kW (27 bhp) with 190 kW (258 bhp) at 6650 rpm. Maximum torque of 300 N·m (221 lb·ft) is available between 2500 and 4000 rpm. The company says the basic unit has the highest specific power output per liter and the highest power/mass ratio in its class at 63 kW/L (84 hp/L) and 1.18 kW/kg (0.717 hp/lb), respectively. At just 161 kg (355 lb), the R6 is 7% lighter than its predecessor, making it the world's lightest six-cylinder engine, says BMW. Power output is up by 12%, with fuel consumption down by 12%—and the lowest specific fuel consumption in its class.

For the first time in modern engine construction, BMW uses magnesium for the engine's crankcase, with the material also employed for the new bedplate and cylinder-head cover. The 7%, or 10-kg (22-lb), reduction in engine mass resulting from use of magnesium and from other lightweight engine components such as exhaust manifolds and camshafts is said to contribute substantially to increased agility and dynamics of future BMW automobiles.

The composite magnesium/aluminum crankcase weighs just 57% of a comparable grey-cast iron block, and has a 24% advantage compared to aluminum. Being the largest single engine component, it makes a significant contribution to reducing total mass.

However, use of magnesium does pose some interesting technical challenges. A crankcase made exclusively of magnesium or a conventional magnesium alloy is inadequate for high-performance production engines; it has insufficient stability and the surface structure of magnesium is unsuitable for the cylinder liners. So the inner part of the R6 crankcase features an aluminum insert that incorporates the cylinder liners and coolant ducts. The insert provides the required stability under the high thermal and mechanical strains of the engine. The cylinder head is mounted directly onto the insert, the lower section of the latter serving as the upper section of the crankshaft mounting. BMW overcame the problem of the chemical incompatibility of magnesium and water by not allowing the coolant to come in contact with the magnesium crankcase shell because it flows exclusively inside the aluminum insert.

The magnesium jacket accommodates the oil ducts, gear casing, as well as most mounts and brackets for ancillary components. The integration of supports and brackets increases stiffness of the ancillary component connection, enhancing the acoustics of the crankcase/ancillary component package. The R6 engine continues BMW's tradition of chain drive of the valves. The company prefers the method because they say it contributes greatly to accurate and durable functioning of the engine and reduced maintenance—and cost—for the vehicle owner. During engine assembly, the chain drive is placed into a chamber at the front of the engine and fixed into place without gear casing bolts and time-consuming sealing of the cylinder head and crankcase.

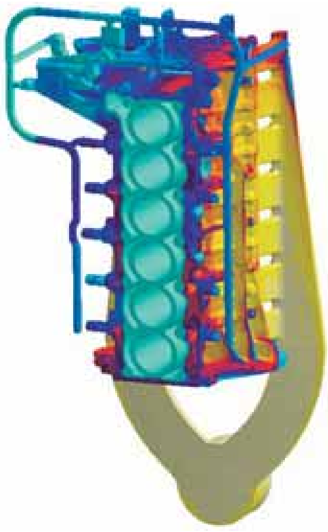
Since the magnesium bedplate functions as a load-bearing engine component of the R6's central frame structure, it also employs composite construction. The crankcase is mounted on the bedplate from above, together with the upper section of the crankshaft bearing. The lower counterpart of the crankshaft bearing is integrated into the bedplate. The crankshaft runs on sintered steel inserts surrounded by magnesium. After the bedplate and crankcase are bolted together, a sealing compound is injected under high pressure between the two components. Due to similar coefficients of expansion, aluminum bolts are used for fixing parts to magnesium components, adding to the reduction in engine mass.

*BMW calls its new R6 3.0-L inline six the most comprehensive engine project since the introduction of its first automobile.*

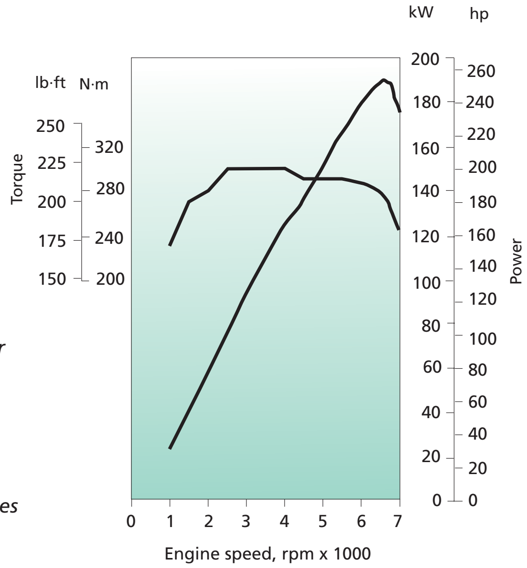
After the aluminum-magnesium crankcase, the new lightweight camshafts are the largest single contributors to the R6's low mass. Hydroforming reduces the mass of each of the two finished camshafts by 25%, or 600 g (21.1 oz). The primary camshaft component, a steel tube, is pulled through the high-strength steel cam rings. The assembly is placed in a die and the tube is subjected to internal water pressure of 4000 bar (58 ksi) to achieve the desired wave shape and pressed against the cams from the inside. Finally, the cams are polished down to a 39-μin finish.

New connecting rods also contribute to mass savings. When viewed from the side, their upper eye is tapered to save a few grams each, which might not seem like a lot but is significant considering the high speed at which the connecting rods

*The R6 crankcase features a magnesium shell around an aluminum insert (image) that incorporates the cylinder liners and coolant ducts.*



*The R6 gets BMW's second-generation Valvetronic for higher engine speeds. The innovation adjusts valve opening times and valve timing infinitely according to accelerator pedal position and eliminates the need for throttle butterflies*



*Peak output of the R6 surpasses its predecessor by 20 kW (27 bhp), with 190 kW (258 bhp) at 6650 rpm. Maximum torque of 300 N·m (221 lb·ft) is available between 2500 and 4000 rpm.*

reciprocate. The lower area of the connecting rod eye is wider so the gudgeon pin can transfer the high forces of the crankshaft via the connecting rod.

Second-generation Valvetronic makes its first appearance on the R6, following implementation of the first generation on BMW four-, eight-, and twelve-cylinder power units. The innovation adjusts valve opening times and valve timing infinitely according to accelerator pedal position. This technology eliminates the need for throttle butterflies and very accurately regulates charge-changing processes, achieving better fuel economy and improved engine response. The hike in rated R6 engine speed and maximum engine speed to 7000 rpm necessitated the system's redesign, specifically for enhanced stiffness. The system now achieves valve actuation acceleration ratings equal to those of bucket tappet valvetrains. It also incorporates more aluminum components, contributing to mass reduction.

BMW believes Valvetronic will be distinctly more successful than lean direct-injection concepts. Employing it on the six-cylinder, the most widely sold BMW power unit, means there will be a quantum leap for this technology's market penetration and the overall fleets' reduction in fuel consumption, regardless of region. In contrast, the full fuel-consumption potential of lean DI systems, for example, can only by exploited in markets with adequate sulfur-free fuel, which is not available in some countries. On average and under all operating conditions, Valvetronic achieves a drop in fuel consumption of 10% in the composite EU cycle.

The cooling system's electric water pump, another R6-first innovation, operates according to the engine's actual cooling requirements, regardless of engine speed. Its use results in a significant reduction in consumption. While a conventional water pump consumes up to 2 kW, the new electric unit needs just 200 W.

For a conventional water pump, cooling capacity is designed to cope with a maximum engine load at low engine speeds and is, therefore, too great for many operating conditions, especially at high engine speeds. It also operates continually via a belt drive, with excessive losses due to friction. Pump flow rate is dependent on engine speed and not on the engine's actual cooling requirements.

During warmup of the engine, its least efficient phase, the electric water pump requires little power. And the residual

| R6 Engine Specifications | |
|---|---|
| Configuration | Inline six |
| Maximum output | 190 kW (258 bhp) at 6650 rpm |
| Maximum torque | 300 N·m (221 lb·ft) at 2500-4000 rpm |
| Combustion | Naturally aspirated, Lambda=1.0, Valvetronic valve control |
| Capacity | 2977 cm$^3$ |
| Compression ratio | 10.7:1 |
| Bore x stroke | 85 x 88 mm (3.35 x 3.46 in) |
| Crankcase material | Magnesium with aluminum insert, Alusil-type liners |
| Distance between cylinders | 91 mm (3.58 in) |
| Conrods | Cracked, trapezoidal |
| Camshafts | Two, chain-driven, hydroformed, in seven bearings |
| Camshaft adjustment | Infinitely variable phase adjustment of intake and exhaust (bi-VANOS and Valvetronic) |
| Valve drive | Roller rocker arms, hydraulic valve play compensation |
| Valves | Four per cylinder |
| Intake system | Three-stage resonance |
| Engine mass (BMW standard) | 161 kg (355 lb) |
| Engine management | Digital engine control with integrated Valvetronic valve management (MSV70) |
| Fuel | 87-98 RON (rated output with RON 98 fuel) |
| Cooling | Electric pump, map-controlled coolant temperature |

heat in the coolant can be used to heat the car's interior with the electric pump even when the engine is not running.

The use of the electric water pump, which operates without a belt, meant that all ancillary components of the R6 could be driven by one belt. The result is reduced engine length and lighter weight since accessory parts such as the belt, belt pulley, and tightener are eliminated.

As with the electric water pump, the engine's capacity-controlled oil pump supplies the specific quantity of oil for given engine operating conditions and consumes up to 2 kW less than conventional oil pumps.

The R6's three-stage air intake system, a development of the previous dual configuration, allows for higher torque at lower engine speeds. The third resonance pipe, which is actuated via resonance valves, effectively increases the engine speed range downward.

BMW engineers threw all their know-how into the exhaust manifold, with a resulting mass reduction of 0.8 kg (1.8 lb). The differing thermal expansion coefficients of aluminum (cylinder head) and steel (exhaust manifold) necessitated new solutions in this particular area. So its lightweight, deep-draw flange is reduced from 12 to 2 mm (0.47 to 0.08 in) and a graphite ring is used on each cylinder to achieve significantly improved tightness to the engine's header. The thin-walled ceramic catalysts are smaller and lighter, so they reach operating temperature faster and eliminate the need for secondary air intake.

A new oil/water heat exchanger transfers heat to the engine oil so that it reaches operating temperature much earlier, shortening the uneconomical warmup phase. Conversely, heat is extracted from the oil circuit by the heat exchanger and from the engine via the coolant circuit during periods of greater engine output and oil temperatures.

*Kevin Jost*

# Yamaha engineers Volvo V8

Physics and market forces are pushing most newly developed engines into very similar configurations as designers seek to optimize power and efficiency in engines that appeal to the broadest array of customers. In some cases there are overriding factors that cause manufacturers to forego the efficiency, balance, or packaging benefits of these popular solutions. In **Porsche**'s case, for example, the heritage of the traditional horizontally opposed engine configuration outweighs other considerations.

**Volvo**'s most prominent core value is safety, so when market forces dictated that an eight-cylinder engine should be offered in its XC90 mid-size SUV, the company faced a challenge packaging a wider transverse-mounted V8 engine in the space of the inline six-cylinder without compromising crush space in the engine bay.

A normal, balanced 90° V8 simply wouldn't fit with the required crush space, the company concluded. Volvo engineers estimated that to use the **Jaguar** V8 would require the XC90 front end to be extended by 200 mm (8 in). The solution would be to develop a new 60° V8. The company's acquisition by **Ford** helped Volvo engineers make the necessary connections, and Ford Chief Technical Officer Richard Parry-Jones pointed them to **Yamaha**, the company that supplied first a high-performance V6 for the Taurus SHO, and later a 60° V8 that was derived from the original six-cylinder.

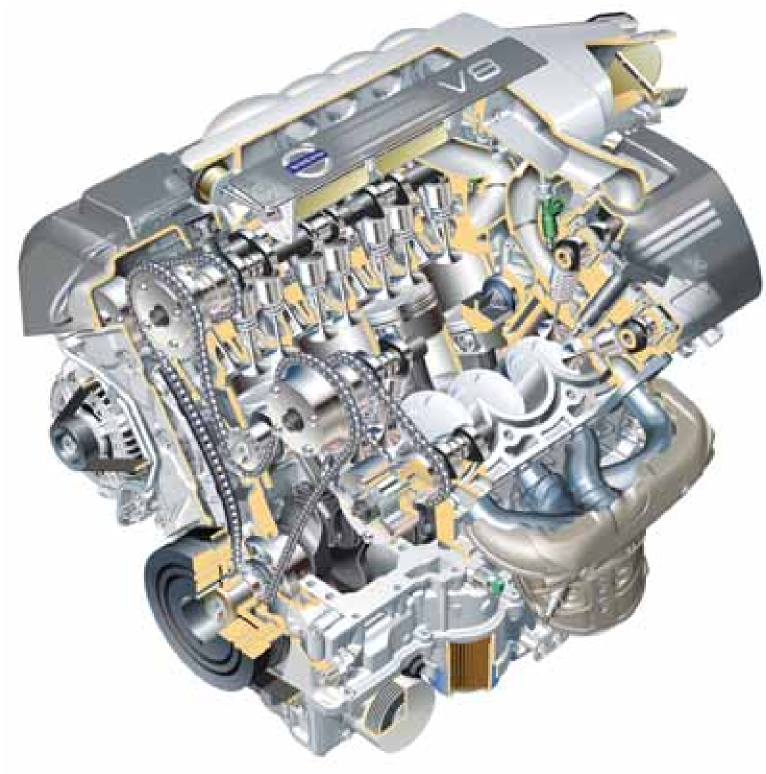
*The compact 4.4-L Yamaha-built 60° aluminum V8 measures only 29.7 x 25 in (755 x 635 mm) and has a mass of 419 lb (190 kg), but produces 315 hp (235 kW).*

"From the very beginning, we knew that it takes a V8 to go all the way in the premium SUV segment," said Kjell Hvarfvén, XC90 V8 Project Director. "We looked for many years for a V8 that would fit, even before Ford bought us."

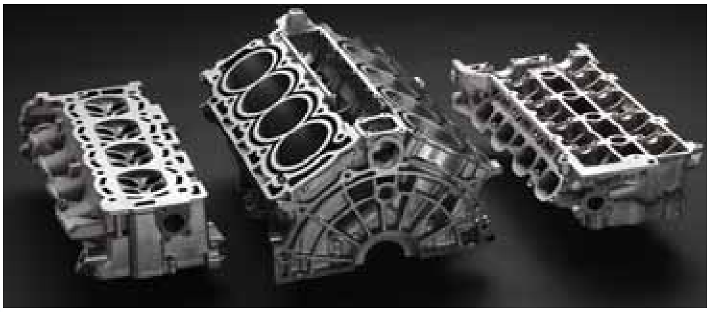
Because Yamaha provides the Volvo's 4.4-L, 315-hp (235 kW), 325 lb·ft (440 N·m), 60° V8, using the same bore spacing and stroke as the old 3.4-L Taurus SHO V8, it would be easy to assume that the XC90's engine is simply a larger-displacement version of its predecessor. But that assumption would be wrong.

While some fundamental dimensions

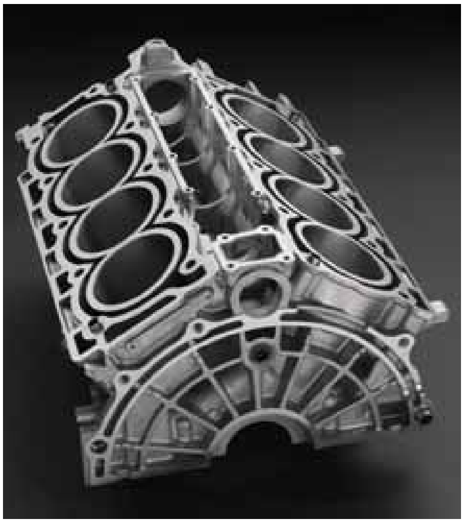
*Volvo determined that only a very narrow 60° V8 would fit in the XC90's engine bay while preserving the requisite forward crumple zone.*



Contributing to the V8's compact dimensions are direct-mounted accessories and exhaust cams that are driven off the intake cams, eliminating the large-diameter exhaust cam gear near the edges of the engine.



*All new cylinder heads feature combustion chambers with a large squish area, which assists in reducing emissions and maximizing fuel efficiency with a lean air/fuel mixture. The block carries its left cylinder bank staggered ahead of the right for packaging reasons in the XC90.*



*The 60° V8's narrow central valley leaves just enough space for the critical balance shaft in the location of an OHV V8's camshaft. The iron cylinder liners are cast into the high-pressure die-cast aluminum block.*

of the architecture are carried over from the earlier engine, literally everything else has changed. The very layout of the block, for example, sees the left cylinder bank shifted ahead of the right, contrary to conventional fashion which places the right bank ahead. The change was made for packaging reasons under the XC90's hood. According to Johan Tollmén, Project Manager, Powertrain Controls, the new Volvo V8 engine owes as much to Yamaha V6 outboard-motor technology as it does to the old Yamaha/Ford engines.

The new engine block is made by high-pressure die casting, rather than the previous gravity casting, to help maintain block integrity. Iron cylinder liners are cast in. Volvo claims that the resulting engine is the smallest V8 on the market, measuring 29.7 in (755 mm) long and a scant 25 in (635 mm) wide. The Yamaha/Volvo collaboration tips the scales at 419 lb (190 kg), only 55 lb (25 kg) more than the inline six-cylinder T6 engine.

A balance shaft spins in the valley of the engine's vee to offset vibration resulting from its inherently unbalanced 60° design. Completely new cylinder heads feature new combustion chambers with large squish areas. "When combustion starts, it is quite slow burning the first 10% of the charge," he said. "Then it is quite fast combustion with very high turbulence." This lets the engine run lean, and do so quickly after start-up, to minimize emissions, according to Hvarfvén.

The lean-burn combustion also contributes to the engine's ULEV-II rating, which fulfills Volvo's other core characteristic, environmental responsibility. Close-coupled catalysts mount to each of the low-thermal-mass stamped sheet-metal exhaust manifolds, and another pair mounted downstream in the XC90 V8's dual exhaust system completes the emissions scrubbing. The catalysts light off within 15-20 s of start-up, according to Hvarfvén, helped by a higher idling speed of 1250 rpm that drops to 675 rpm when the engine is warmed up.

The valvetrain is also all-new, with variable cam timing for both the intake and exhaust cams, allowing as much as 40° of variation on each, and shimless tappets act on the valves for simplified assembly. Volvo maintains optimum intake flow with a crossover valve that opens between the left and right halves of the intake plenum. Above 3200 rpm, the valve opens, letting cylinders draw air from the entire volume of the plenum chamber during high-speed operation.

The engine's castings feature built-in mounts for all accessories, eliminating the space consumed by bracket-mounted accessories, along with the resulting noise. Both AC and power-steering pumps use variable-displacement technology, which Volvo engineers estimate reduces the fuel consumption by about 4%

Working with Japanese engineers thousands of miles away posed no particular hardship for the Volvo team, according to Hvarfvén. "We are actually quite used to working with Japanese suppliers," he said. "**Denso** supplies Volvo's engine management system, and **Aisin-Warner** has provided the company with transmissions since the 1980s."

*Dan Carney and David Alexander*