The new Blackwing V8 Engine in the Cadillac CT6 V

In this article, General Motors presents its new Blackwing V8 direct injected gasoline engine with 4.2 l displacement, double overhead camshaft architecture and twin-turbocharging, which is exclusively used in the Cadillac CT6 V luxury sedan. Development targets were high torque at low and medium engine speed and high power at the upper end of the speed range. The engine is designed to meet the requirements for use in a high-performance sedan; particular attention was paid to good responsiveness.

STARTING POINT

Modern vehicles have experienced a rapid expansion in feature content as the price of computing power drops and consumer expectations rise. The added components spread throughout the entire vehicle – including the engine compartment. Added packaging space is required for advanced braking systems, all-wheel-drive transaxles, noise abatement insulation and resonance volumes, and advanced passenger comfort systems taking away space traditionally available for the powertrain. As such, new and innovative designs are needed to create a more compact engine to fit in the space available.

One concept which has become more common in luxury vehicles is a turbocharged V8 engine featuring valley mounted turbochargers. This concept provides the benefits of a low volume exhaust system that reduces turbo lag as well as compact packaging to fit in the ever smaller space under the hood. With the design freedom of a completely new engine architecture available to the team, General Motors (GM) decided early in the program to adopt the valley mounted turbocharger concept. This enabled the development team to simultaneously meet the transient response, peak torque and peak power targets. In addition, every aspect of the engine, from block height to the connecting rod

TABLE 1 Engine performance (© GM)

Maximum power	[kW]	410 at 5000 rpm (SAE certified)
Maximum torque	[Nm]	867 at 3400 rpm (SAE certified)
Low speed torque	[Nm]	650 at 2000 rpm
Maximum engine speed	[rpm]	6100
Emissions certification	[–]	ULEV/125

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bearing diameter, was scrutinized for maximum density without sacrificing the engine's performance or durability and robustness.

ENGINE CONCEPT

The Blackwing is an entirely new 90°-V8 engine intended for the Cadillac CT6. The main focus during the development was on an effortless driving feeling due to a high torque even at low speeds. Key performance targets for the engine are shown in **TABLE 1**.

The vehicle architecture of the CT6 is based on the use of a four-cylinder in-line engine and a 60°-V6 as the primary drive sources. This made packaging of a turbocharged V8 with four overhead camshafts a huge challenge in both width and height. The engine is only available in an all-wheel drivetrain further limiting the underhood space for the engine. As a result, the only 90°-V8 twin-turbo engine concept that would fit in the vehicle was one where the exhaust and turbochargers were located in the center of the valley with the intake ports on the outside of the cylinder head. **FIGURE 1** illustrates how compact the resulting engine package is for the Blackwing V8. Key engine specifications can be found in **TABLE 2** and are presented in detail below.

CYLINDER BLOCK

The cylinder block is a precision sand cast, deep skirt construction from A319 aluminum with a T7 heat treatment (solution heat-treated and over-hardened/stabilized; improves fracture toughness and resistance to stress cracking and layer corrosion [1]). The cylinders feature pressed-in iron liners while the four-bolt nodular iron main bearing caps have an additional cross bolting to the skirt to make a stable structure capable of handling 25.4 bar BMEP.

Given the space available for the engine and all wheel drive differential, every subsystem within the engine was scrutinized for packaging space. For a cylinder block using iron liners, a relatively narrow 96 mm bore spacing and an optimized deck height of 215 mm was achieved. To make the reduced deck height of the cylinder block possible, the outer fasteners for the main bearing cap are angled by 13°. This enables the proper thread engagement for the fastener without encroaching on the piston at bottom dead center or breaking out

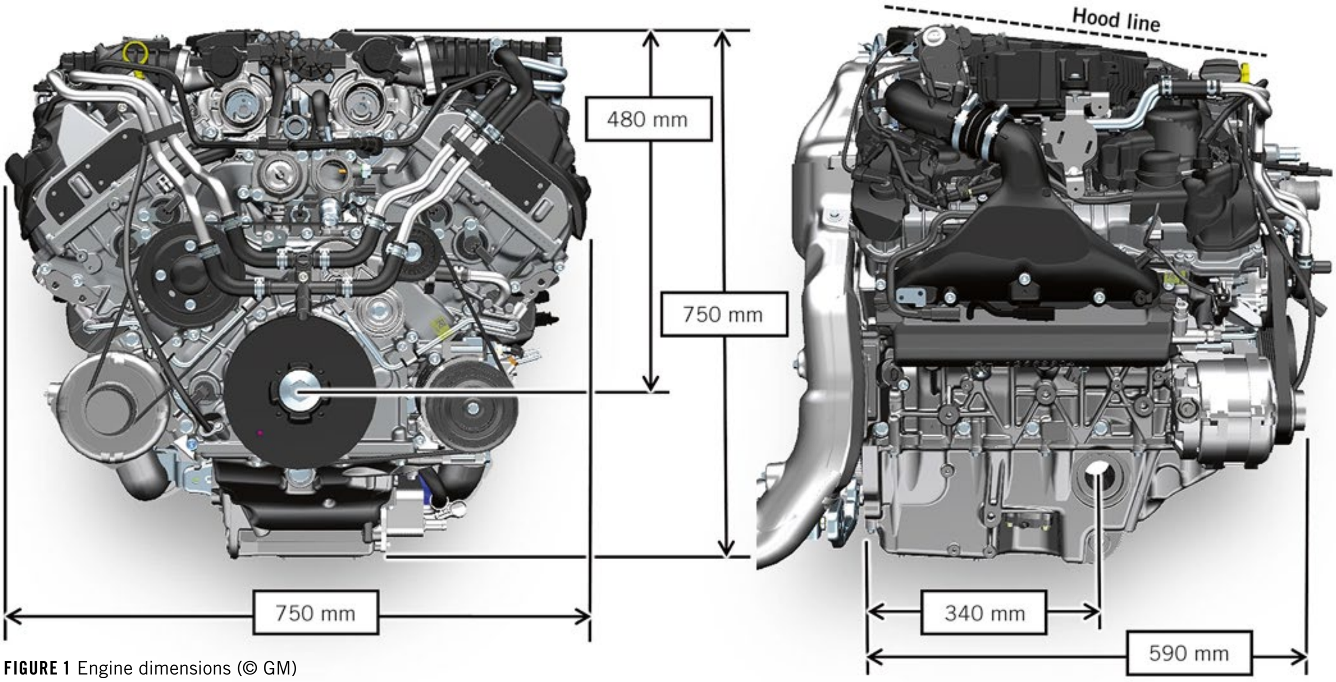


FIGURE 1 Engine dimensions (© GM)

Engine configuration	[-]	90° V8
Displacement	[l]	4.192
Bore	[mm]	86
Stroke	[mm]	90.2
Compression ratio	[-]	9.8 : 1
Cylinder block	[-]	Sand cast A319 aluminum, deep skirt with cross bolted MBC, iron pressed-in liners
Cylinder spacing	[mm]	96
Cylinder bank offset	[mm]	20.9
Deck height	[mm]	215
Cranktrain	[-]	Forged steel crankshaft with tungsten inserts
Main/rod bearing diameter	[mm]	72/50.8
Power cell	[-]	Forged steel connecting rod
Connecting rod length	[mm]	139.3
Piston comp height	[mm]	30
Cylinder head	[-]	Rotocast A356-T6 aluminum
Valve train	[-]	Four-valve Type 2 DOHC system
Active fuel management	[-]	Cylinder deactivation by collapsing RFF
Intake valve diameter	[mm]	36
Intake valve lift	[mm]	10.87
Exhaust valve diameter	[mm]	29
Exhaust valve lift	[mm]	10.47
Intake dystem	[-]	Aluminum intakes with dual throttle bodies
Charge air coolers	[-]	Two engine mounted water-to-air coolers
Exhaust system	[-]	Integrated exhaust manifolds and turbine housings
Turbochargers	[-]	Two valley mounted twin scroll turbos with electric wastegate controllers
Catalysts	[-]	Two valley mounted single brick catalysts
Lubrication system	[-]	Fully variable oil pump with wet sump
Starting system	[-]	Start/stop enabled with engine starter
Fuel system	[-]	350 bar direct injection (side mounted)
Fuel type	[-]	98 RON gasoline

TABLE 2 Key specifications of the Blackwing engine (© GM)

into the hone over travel clearance reliefs, **FIGURE 2**.

With uneven cylinder filling as an inherent trait of cross-plane crankshaft V8s, it is critical to optimize the cooling of the combustion chamber in order to minimize the knock tendencies of the engine and ensure its durability. With respect to cooling the top of the cylinder bores, a stepped drill was used to flow coolant between the cylinders. This drill directs the coolant from the cooling jacket in the cylinder block to that of the cylinder head. A metering hole in the head gasket is used to regulate the coolant flow, enabling the coolant flow in each cylinder to be metered individually with a unique orifice size based on the temperatures of each cylinder.

CRANKTRAIN AND COMBUSTION CHAMBER

The space available for cranktrain and combustion chamber was limited by the location of the all-wheel drive transfer housing, available packaging space for the starter, and low deck height of the cylinder block. As such, the cranktrain had to be optimized to fit within the given package. For this purpose, the rod bearing diameter was reduced as much as possible to make a small rod path while the main bearing diameter was increased to recapture the required overlap for crankshaft stiffness and strength. The sizes of the bearings plotted on the FEV scatterband in **FIGURE 3** show how the crankshaft was tailored to fit the packaging constraints of the application.

As the deck height of the engine was minimized in combination with the relatively long stroke and double overhead camshaft architecture, the combustion chamber was scrutinized for minimal length at top dead center. Optimization of the combustion chamber overall length resulted in a short connecting rod that gave an L/R ratio (l = rod length, r = crank radius) of 3.89. To illustrate how compact this package is, the rod length versus engine stroke for the new V8 engine is plotted on the FEV scatterband in **FIGURE 4**.

The connecting rod is guided by the piston instead of the crankshaft. By reducing the size and relative speed

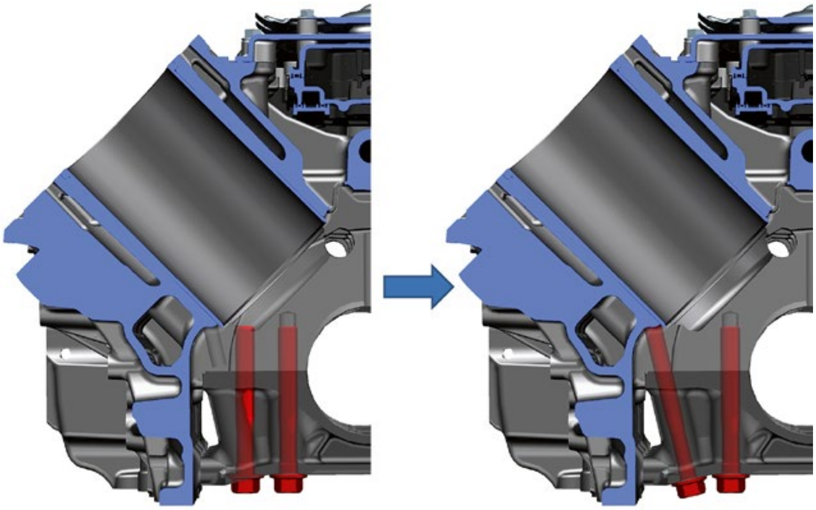


FIGURE 2 Transparent view of angled outboard main bearing cap fasteners (© GM)

of the bearing area guiding the connecting rod, a reduction in overall friction has been achieved.

As with the connecting rod, the piston assembly was scrutinized for reduction in compression height. This began with minimizing the piston pin diameter to 22 mm, below the standard target for an engine with the specific torque of the Blackwing. A DLC coating has been added to the pin to provide better friction and additional durability margin. The ringbelt was then minimized to provide a 30 mm compression height while still maintaining a fully supported three-piece oil control ring.

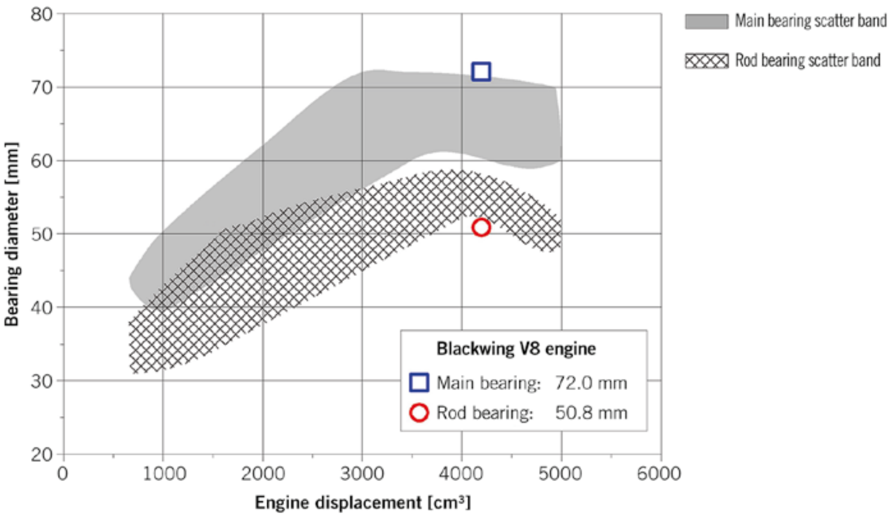


FIGURE 3 Main and rod bearing diameter (FEV database) (© FEV)

CYLINDER HEAD

The cylinder heads are rotocast from A356 aluminum with a T6 heat treatment (solution heat-treated and artificially aged [1]). The team selected this process as it enables superior mechanical properties which are beneficial on a high BMEP engine such as this.

The combustion system was carried over, in part, from the previously introduced LGW engine – a 3.0-l twin-turbo V6. This required several modifications for incorporation into the Blackwing engine with its valley mounted exhaust. The most prominent was the entrance angle of the intake port which had to be curved upward to facilitate the outboard mounted intake manifold while smaller changes in the throat area were also made. A comparison of the Blackwing V8 and LGW inlet ports is shown in **FIGURE 5**.

Although the combustion system started with a proven porting and chamber arrangement, the upward turned entry of the intake ports drove additional development work. Further changes included lowering the exhaust port outlet closer to the head deck and shortening the exhaust runner in the cylinder head to improve package space for the valley mounted turbochargers and minimize exhaust system volume for optimal transient response. The work resulted in a simultaneously improved flow and tumble, which is the twist around an axis perpendicular to the cylinder axis.

Significant Computational Fluid Dynamics (CFD) development of the intake port, combustion chamber, and piston crown was used to develop a new concept for the combustion system, in which increased fresh air flow is directed from the short turn side of the valve early in the intake stroke to push exhaust residuals out of the chamber before the traditional tumble over the front of the valve is developed. This allows the cylinder-to-cylinder imbalance due to valve overlap in cross-plane crank V8 engines to be compensated. The charge motion early and late in the intake stroke can be seen in **FIGURE 6**.

The exhaust ports were also modified from the original LGW concept. The port was lowered and the exhaust manifold mounting face was pushed closer to the cylinder in order to reduce overall exhaust system volume and provide more space for the packaging of the turbocharger in the valley.

Extensive work was done to facilitate the cooling of the cylinder head with a single-piece cooling jacket. Although such cooling jackets are relatively conventional, the inboard mounted exhaust ports required a unique coolant flow circuit. In order to achieve a high coolant flow rate through the exhaust valve bridge area, the majority of the coolant is directed from the block into the cylinder head under the exhaust ports, as is the case for most conventional engine arrangements. However, in order for the cooling jacket to degas during coolant fill and in operation, the coolant also exits the cylinder head on the exhaust

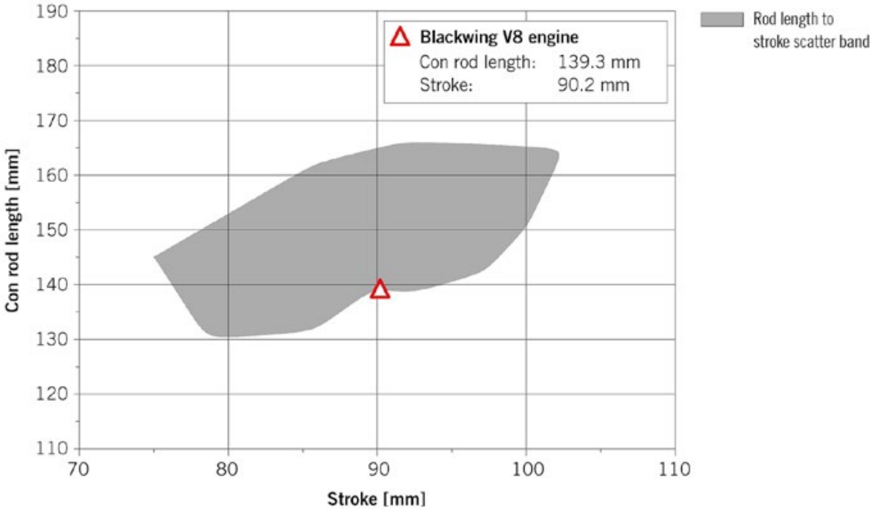


FIGURE 4 Connecting rod length compared to engine stroke (FEV database) (© FEV)

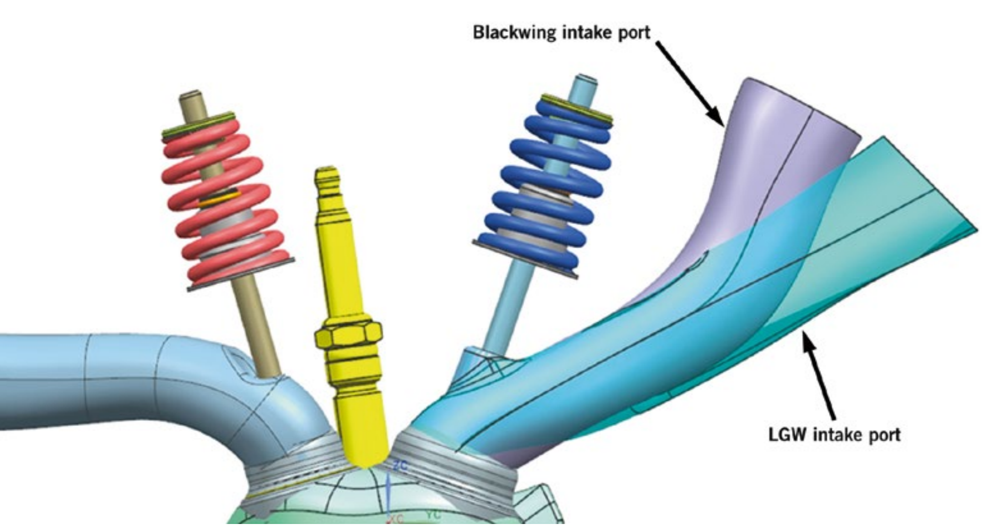


FIGURE 5 Comparison between LGW and Blackwing V8 intake porting (© GM)

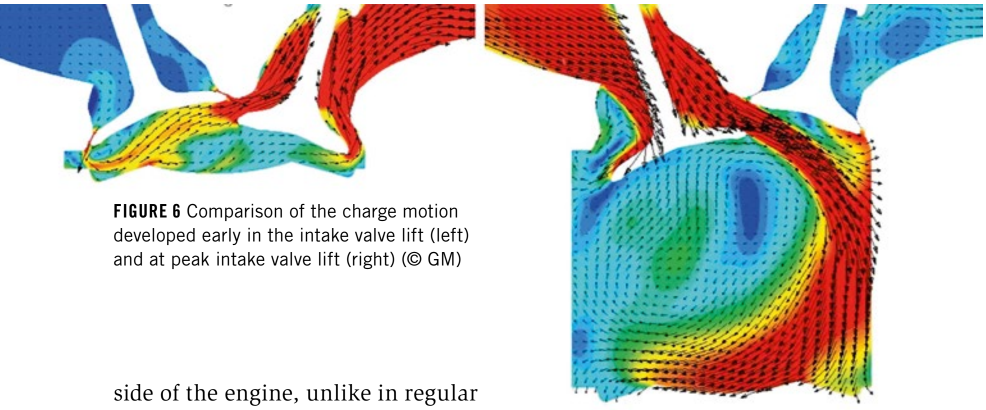


FIGURE 6 Comparison of the charge motion developed early in the intake valve lift (left) and at peak intake valve lift (right) (© GM)

side of the engine, unlike in regular engines, as that is the highest point in the cooling circuit. Thus, the coolant path is designed to enter under the exhaust ports, flow across the combustion chamber, then turn 180° to flow back over the exhaust ports where it is collected and returned to the radiator at the front of the engine. Several designs were investigated using CFD during the development process to ensure that all areas of the head received adequate cooling with a conventional volume coolant flowrate.

VALVE TRAIN AND TIMING DRIVE

The valve train was conceptually carried over from the LGW V6 engine with key changes to fit the packaging requirements of the Blackwing V8 engine and implement an eight- to four-cylinder deactivation strategy. The collapsing roller finger followers are actuated via hydraulic pressure that is controlled by cam cover mounted solenoid valves.

The development team implemented a cam carrier system to simultaneously reduce friction and provide packaging space for the switching roller finger followers required for cylinder deactivation. This die-cast carrier is complex and houses the camshafts as well as the high pressure fuel pump, and provides worm trail lubrication passages for the cylinder deactivation switching mechanisms.

INTAKE SYSTEM AND CHARGE AIR COOLING

In order to achieve a crisp throttle response and a fast time to low end torque, the intake volume was minimized by locating the water to air charge air coolers over the cam covers. The intake manifolds are fed directly out of the charge air coolers and cascade over the intake cam side of the cylinder heads into the intake ports. This compact packaging of the intake system resulted in an intake system volume of approximately 6.8 l from the compressor outlet to the intake valves, and just 4.3 l of that volume are throttled. This compact system, in combination with the low volume exhaust system achieved with a valley mounted turbocharger, was critical to achieving the throttle response targets of the engine without sacrificing the high power targets, which requires relatively large turbochargers.

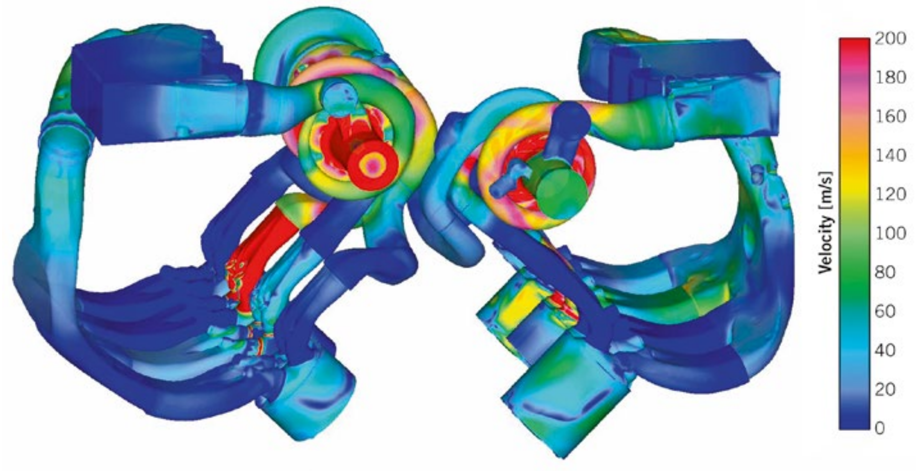
Particular attention was paid to the design of the intake tract such that the charge air coolers were well utilized without the need for restrictive features such as turning vanes. Due to the bank offset of the engine and unique packaging constraints on each side, the charge air coolers were not located in the same position. This required the development of two unique intake tracts with both paths optimized for cooler utilization while maintaining similar volumes. The resulting charge air cooler utilization was above 90 % for both banks ensuring a balanced charge air temperature for each manifold.

With the charge air coolers being prominently located on the top of the engine, styling cues were included in the housings of each cooler including a “hand crafted with pride” plaque that is customized and installed by the engine builder on the right charge air cooler. The coolers and the aluminum top cover give a striking engine appearance when the hood is raised.

TURBOCHARGING AND EXHAUST SYSTEM

The engine features two twin-scroll turbochargers that are controlled by electric wastegate actuators. The turbochargers have integral exhaust manifolds that minimize exhaust volume. This volume, approximately 2 l for both banks combined from the exhaust valve to the turbine wheel, and the compact intake system provide an extremely low volume airflow path for improved transient response. **FIGURE 7** illustrates how compact the complete airflow path is for both the intake and exhaust. Even though the cross-plane V8 does not supply the turbochargers with evenly spaced combustion pulses, the twin-scroll turbochargers combined with a low volume exhaust system provides significant transient response and full load benefits

FIGURE 7 Gas velocities of the complete airflow path of the 4.2-l twin-turbo engine (© GM)



without sacrificing the favorable classic V8 NVH characteristics.

The valley mounted exhaust manifolds, turbochargers, and catalysts lead to significant thermal challenges under the hood. As thermal management was a top concern during the development in order to achieve high robustness, several heat shielding and valley cooling strategies were tested with multiple strategies implemented. These include direct thermal protection of sensitive components, targeted airflow and heat flow paths as well as various heat shields. The exhaust manifolds and integrated turbine housings are insulated with contact heat shields. It turns out that the contact heat shields with fiber insulation and metallic outer shell provided the best thermal management and required the least packaging space. The turbo and manifold heat shields are pre-attached to the parts, simplifying assembly sequencing of the hardware in the valley.

FUEL SYSTEM

A 350 bar direct injection fuel system was selected to minimize particulate emissions and enable fast combustion at high injection quantities. This system features two intake cam driven fuel pumps with side mounted injectors outside of the valley. Each intake cam features three lobes to drive the pumps. Multi-body analysis of the camshaft drive system and dynamic pressure simulation of the fuel system were conducted to ensure durable operation in combination with optimal engine performance. To meet program targets, the three lobe camshafts were found to better time the fuel pump pulses between the valve events to reduce the peak loading on the timing drive while still providing a consistent fuel delivery.

LUBRICATION AND CRANKCASE VENTILATION SYSTEM

At the heart of the lubrication system is a continuously variable vane oil pump. It is driven by the nose of the crankshaft and features a pulse-width modulation controlled solenoid valve that is used to control the eccentricity of the oil pump.

The crankcase ventilation system features a valley mounted two-stage oil separator that has dedicated drains at the rear of the engine for the coarse separator and at front for the fine separator where the separated oil is returned to the oil pan. These drains end below the oil level in the oil pan to prevent crankcase gases from short circuiting the separator.

The fine separator oil drain is located in a relatively shallow portion at the front of the oil pan. In order to prevent the drain from being uncovered during hard acceleration or cornering, a unique, patent pending design was developed. This design incorporates a reservoir located around the exit of the drain. This feature was implemented in a cost-efficient manner by using one drill for the oil drain and another one for creating the reservoir, **FIGURE 8**.

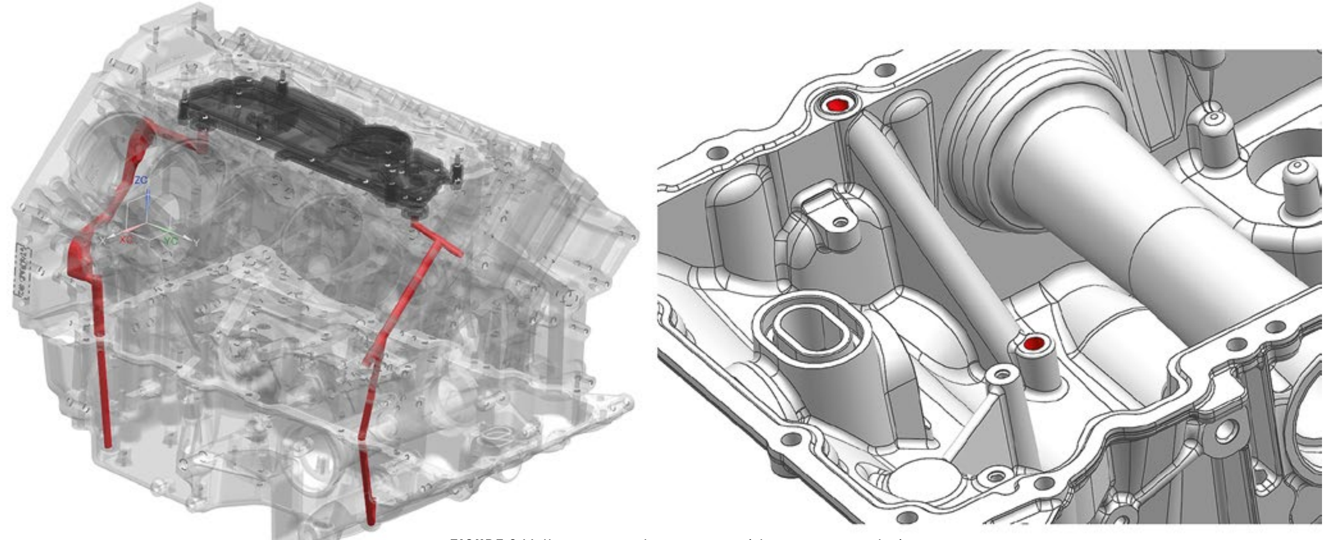


FIGURE 8 Valley mounted separator with rear coarse drain and patent pending front fine separator drain (© GM)

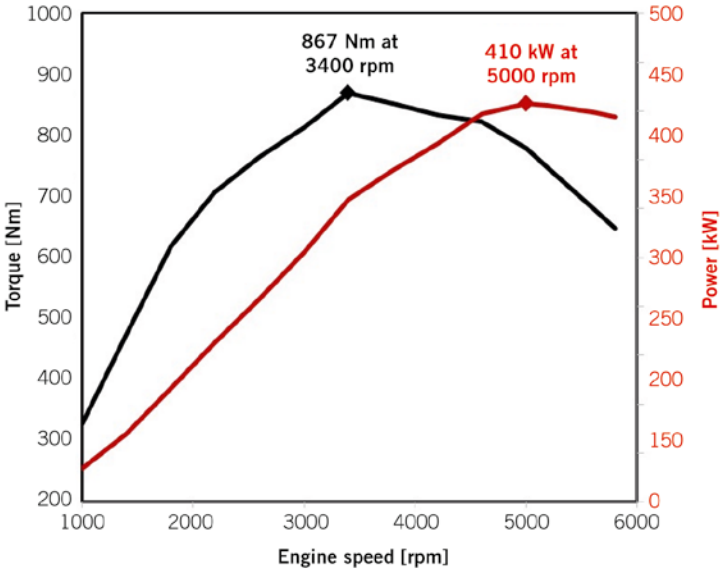


FIGURE 9 Torque and power curves of the Blackwing V8 engine (© GM)

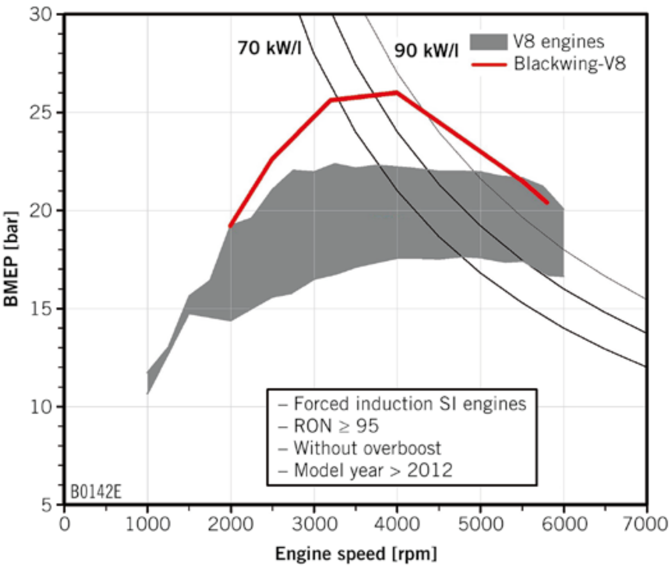


FIGURE 10 BMEP comparison to benchmark engines (FEV database) (© FEV)

ENGINE PERFORMANCE

The engine exhibits class leading performance as can be seen by the power and torque charts, **FIGURE 9**. The peak torque is 867 Nm at 3400 rpm with more than 800 Nm available from 2800 to 4800 rpm. The maximum power of 410 kW is at 5000 rpm and is SAE certified. The high low-end torque combined with the wide peak torque range ensures the sovereign driving feeling postulated in the development goals. The torque density of the engine is impressive and significantly above other cross-plane crankshaft V8 engines, **FIGURE 10**.

The results illustrate that this Blackwing engine meets the requirements of a performance sedan while simultaneously providing a very good responsiveness.

REFERENCE

[1] Gesamtverband der Aluminiumindustrie e. V.: Wärmebehandlung von Aluminiumlegierungen. Online: http://www.aluinfo.de/files/_media/dokumente/Downloads/Technische%20Daten/Merkblaetter/W7_Waermebehandlung_von_Aluminiumlegierungen.pdf, access: March 07, 2019