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Supercharging Ford's 4.6L for Affordable Performance

Brian J. Roback and Matthew R. Holl
Ford Motor Company

Michael L. Eble and David Thornton
Roush Industries, Inc.

ABSTRACT

This program was to provide the Mustang performance customer a powerful, affordable engine, while minimizing the impact on manufacturing at the engine and vehicle assembly plants. Variations of engines that met the manufacturing requirements were evaluated, and only the supercharged, 4-valve per cylinder 4.6L engine satisfied all the criteria. This paper covers the changes required to the engine system and the development efforts to meet program requirements. The final results are compared to previous engines in the vehicle, and to other supercharged engines.

INTRODUCTION

Customer research had shown that there was enough interest in increased power levels that an engine system that matched the special purpose "R" version of 2000 should be developed that was more manufacturing friendly. An engineering team was established representing design, development, testing, and manufacturing. Roush Industries, Inc. was the tier one supplier for outside sourced product integration.

Previous studies[1] had shown that the 4.6L engines were capable of producing 600 Horsepower (Hp) (450 kW) in naturally aspirated racing form. Several workhorse vehicles were built to evaluate the performance feel and emission capability of candidate engines. These results did not meet the program objectives, primarily due to lack of low speed engine torque. The historic muscle car engines had displacements of up to 7.0L, and matching this performance with much smaller displacements was going to require boost.

Experience with supercharging the 5.4L engine led to studies of the various 4.6L configurations. While it was possible to provide the required low engine speed torque with the supercharged 4.6L 2-valve engine, the higher speed performance didn't meet the objectives. Thus a decision was made to use a supercharged 4.6L 4-valve engine for the Mustang Cobra.

This paper discusses the engineering methods used and results obtained in a program to provide an improvement of 22% in power compared to the previous engine without major change to manufacturing of the engine or vehicle. The planned program duration was 20 months from engine configuration decision to vehicle Job #1.

OBJECTIVE

The engine program objective was to meet the power levels of historic muscle cars with an engine system that could be built on the existing engine assembly line and installed on the existing vehicle assembly lines. The vehicle had to meet all the 2003 model year legislative requirements, and provide the quality, reliability, and economy expected by today's customer. A vehicle Job #1 of May 6, 2002 was established.

OUTLINE OF CHALLENGE

The initial vehicle package reviews and analysis of manufacturing constraints at the engine and vehicle assembly plants eliminated the options of using other engines or turbocharging the existing engines. Timing and budget constraints required maximum use of current facilities and designs.

The challenge was to increase the performance of the existing 4.6L 4-valve engine to meet customer desires, while minimizing the impact to the engine and vehicle assembly plants.

A previous paper[1] had shown that a racing version of this engine was capable of 600 hp (450 kW) at 9000 revolutions per minute (rpm) in racing trim. Analysis found that increasing engine speed above 6500 rpm would have an adverse impact on a number of system components. These components could not be easily redesigned for the higher speeds without major assembly impact. Most component locations were fixed by the need to share manufacturing processes and tools with the existing engines.

Pass-by noise requirements and assembly needs precluded significant reductions in either inlet or exhaust systems restrictions.

METHOD OF APPROACH

Once the objectives were established and the challenges were identified, the process to resolve the issues was developed. An engineering team was established representing design, development, testing, and manufacturing. The team analyzed various alternatives for improving engine performance within the established limits. Workhorse vehicles with parts representing those most likely to meet the objectives were built and evaluated. Comparisons were made between the best naturally aspirated package and the customer desired attributes. The testing indicated that the performance was not meeting the wants of the customer.

The analysis of the 1999 U.S. market [2] had shown that the average bmep increase for supercharged engines was 14 percent. Internal analysis of the 4.6L engine indicated that 22 percent was possible. A study of each component impacted by the increase in cylinder pressure and the increased power levels was completed.

For each part that had issues, the part was either redesigned or the engine performance was tailored to resolve the issues. Test engines were built to validate the various analyses, and first dynamometer and then vehicle testing were performed. Results of the testing were used to make changes in engine performance or component changes.

The final design level was built at the assembly plants, then tested to validate that the design met the required performance, quality, and reliability. Emissions, driveability, sound levels, and fuel economy were confirmed. Based on the results of this testing, the vehicle was approved for production.

PERFORMANCE

The Mustang Cobra has a long history of performance engines. The 1968 7.0L CobraJet established a baseline for future engines with 335 hp (250 kW). As the requirements for emissions, fuel economy, and affordability became more stringent, the use of displacement to provide increased power was limited. The supercharged 4.6L 4-valve design was able to provide 390 hp (290 kW) from 4.6L. Figure 1 shows the power output comparisons for various Mustang engines from 1968 to 2003. The supercharged 4.6L 4-valve design provides more than double the horsepower of the base 3.8L engine.

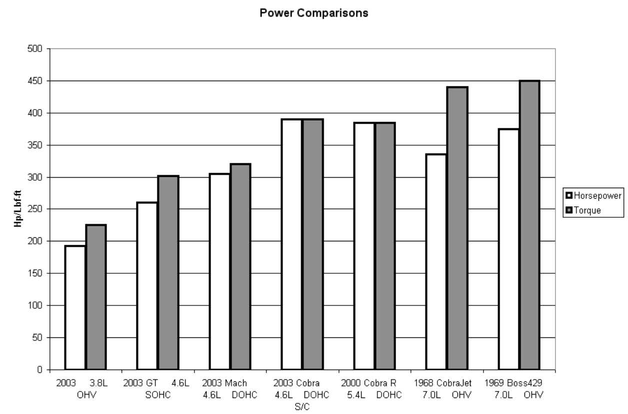

Figure 1: Current power levels compared to historic offerings

To achieve the desired performance numbers the absolute in-cylinder performance was increased, as shown by the brake mean effective pressure (bmep) levels in Figure 2. The package efficiency was also improved as shown in the horsepower per liter (hp/L) comparison.

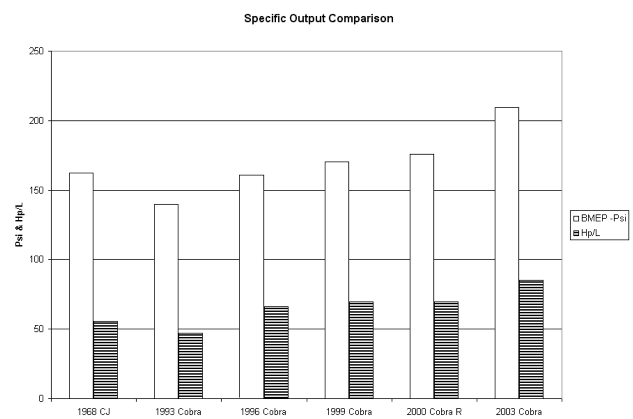

Figure 2: Historic Cobra specific output comparisons

The engine would be in the middle of the 2003 U. S. market supercharged engine bmep range (Table 1)[3,4].

Disp – L	Hp – adv.	Hp/L	Tq – lbf-ft	Bmep-psi
4.2	390	93	399	235
4.6	390	85	390	210
4.0	358	90	372	230
3.2	349	109	332	256
3.8	240	63	280	182
3.3	210	64	246	184
2.3	192	83	200	215
1.6	163	102	155	239

Table 1. Performance - 2003 U.S. Market Supercharged Engines

Figure 3. Engine assembly

ENGINE DETAILS

The starting point for development of the engine was the naturally aspirated aluminum block version of the 4.6L V-8 with 4 valves per cylinder. This engine had been used in earlier models, and development had continued to increase performance. The major work for package and manufacturing were complete; and candidate components were selected to demonstrate the performance available. Cylinder heads, camshafts, intake and exhaust manifolds, air cleaner system, and pistons were all selected for their performance enhancement. A workhorse vehicle was built to simulate the design and evaluated. It was decided that multiple performance options were desired and that an engine line-up of 3.8L, 4.6L 2-valve, 4.6L 4-valve, and supercharged 4.6L 4-valve should be available.

Parallel design and manufacturing studies were undertaken to study larger displacement through increasing bore, stroke, or number of cylinders. But all would require major changes to manufacturing that could not be contained. Turbocharging had package issues that could not be resolved due to close fit of the four-valve engine in the car.

Supercharging was the alternative that could meet all the objectives[5], if the component analysis indicated they could take the increased power. Modal analysis showed that the desired power could be achieved at engine speeds below 6500 rpm, with cylinder pressures below 1400 psi. This would require intercooling, but allowed use of production cylinder heads.

Configuration	Longitudinally mounted 90-degree V-8.
Bore x Stroke	90.2mm x 90.0mm
Displacement	4.601cc (280cid)
Compression Ratio	8.5:1
Horsepower	390 hp (290 kW) @ 6000 rpm
Torque	390 lb.-ft. (529 N-m) @ 3500 rpm
Specific Output	84.8 horsepower per liter
Redline	6500 rpm (fuel shut-off)
Valvetrain	Chain driven double overhead camshafts, roller finger followers with hydraulic lash adjustment
Intake valves	2 per cylinder, 37mm head diameter
Exhaust valves	2 per cylinder, 30mm head diameter
Fuel system	Sequential electronic fuel injection, dual fuel pumps

Ignition system	Distributorless coil-on plug
Induction system	Eaton Corporation M112 Generation IV Roots-type supercharger with water-to-air intercooler, 8.0 psi (0.55 bar) maximum boost pressure
Crankshaft	Forged, fully counter-weighted steel
Pistons	Reinforced pin boss, forged aluminum, dished, anti-friction coated skirt, anodized crown to top ring
Piston pin	Upgraded, improved finish
Connecting rods	H-beam, forged steel
Flywheel	Aluminum, 11 inch (279 mm) single plate clutch

Table 2. Engine specifications

SUPERCHARGER & DRIVE

A positive displacement roots-type supercharger with internal bypass was selected based on the engine airflow needs. Twisted rotors, as described in a previous SAE paper[6], were used. Various combinations of supercharger size and drive ratio were evaluated to provide the best mix of performance and efficiency. The final choice of components provided a maximum boost of 8.0 psi (0.55 bar). This design is self contained, not requiring external oil or cooling. The bypass is controlled through a vacuum motor.

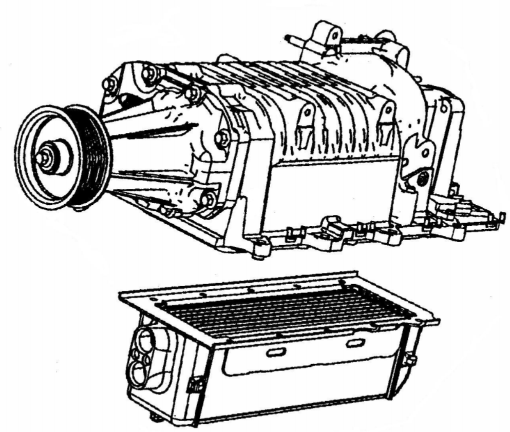

Figure 4. Supercharger and intercooler

SUPERCHARGER IMPACT ON SOUND QUALITY

The first engines built were evaluated for performance feel. During these evaluations, it was noted that the historic muscle car feel was there but the muscle car sound level was not achieved at heavy load conditions. Detailed NVH analysis[7] found that the supercharger system had a significant effect on sound quality. Analysis of the low frequency order levels showed that the sound was not as powerful as the naturally aspirated versions. Powerful sound "can be characterized as having strong ½ order beating. Beating occurs when two or more adjacent orders have similar amplitude levels. Orders like 2.5, 3.0, 3.5, and 4.0 of similar amplitude can create a sound that gives the impression of a powerful engine. This characteristic is not well defined on the" supercharged vehicle. Most of the driver impression was based on intake and exhaust contributions from the engine compartment. Due to the increased stringency of legal noise constraints, tailpipe sound levels played a lesser role. The ½ order beating amplitudes for 2.5, 3.0, 3.5, and 4.0 orders were not as well defined after adding the supercharger system compared with the naturally aspirated engines. The supercharged engine also had a high sound content at the 12, 18, 24 … orders. This resulted in a unique sound for this vehicle, dominated by the supercharger system with little contribution from the exhaust system.

INTAKE & FUEL DELIVERY SYSTEM

The use of a supercharger allowed a much simpler intake design than required for optimum naturally aspirated performance. A "bathtub" manifold was designed that allowed the supercharger, intercooler, and fuel system to be assembled and tested prior to being installed on the engine. This eliminated a major concern in the engine assembly process. Injector angles were optimized for both low and high air flow conditions. Injectors were sized to handle the increased fuel flow required by the increased power output. The intake manifold was designed for significantly increased stiffness to help control supercharger noise levels.

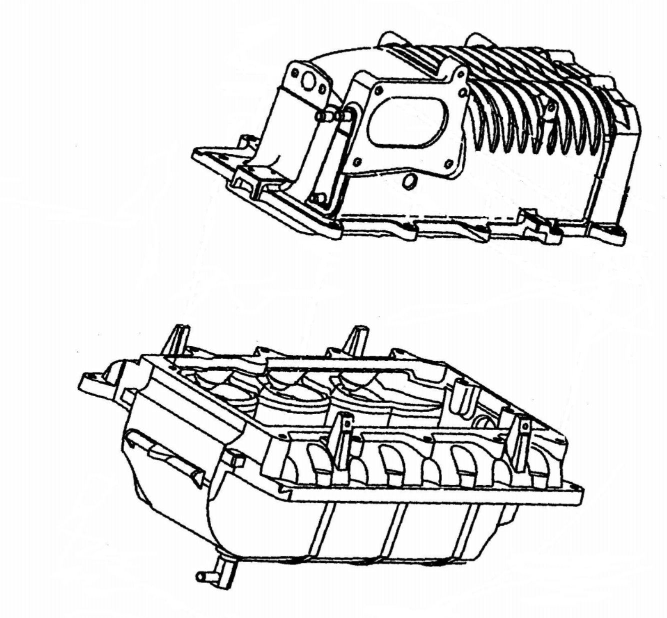

Figure 5. Supercharger and intake manifold

PISTON & ROD ASSEMBLY, CRANKSHAFT

A forged steel, fully-machined, H-beam rod designed to handle 1900 psi (131 bar) combustion pressure was substituted for the standard powdered metal connecting rod. Upgrading was also required for the rod bolt, with larger size and higher strength. The piston pin, piston pin boss, and bushing were upgraded for the higher cylinder pressures.

Although the bore was unchanged from the normally aspirated 4.6L, the piston profile was changed to accommodate the increased combustion pressures and temperatures. The new piston was also upgraded from cast to forged aluminum. A nominal compression ratio of 8.5:1 was selected along with the 8 psi (0.55 bar) to balance performance requirements with engine durability. A Napier ring pack was implemented for oil consumption control based on evaluation of a test engine with two styles of ring packs.

Balance and stress analysis showed that a forged steel crankshaft was suitable. The bob weights were revised due to the reduced weight of the piston and rod assembly.

CYLINDER BLOCK

Analysis of the cylinder block showed that a production cast iron block would be preferred to handle the increased loads from both cylinder pressures and the supercharger drive loads. An aluminum block design was studied, but the changes desired could not be implemented within budget in the time available. The iron block was modified by machining the center main bulkhead to accommodate the fully counterweighted crankshaft. For improved oil consumption control, the bore hone process went from plateau to peak.

Computer Aided Design (CAD) Journal Orbit Analysis (JOA) found that the maximum load of 9757 pounds (4426 kg) @ 3000 rpm on the number 2 main bearing was well within the acceptable range for the block.

CYLINDER HEAD, GASKET & BOLTS

A production cylinder head from another engine program was selected to meet the program objectives. The head is an aluminum open chamber configuration with 4 valves per cylinder. It has revised exhaust port geometry for improved flow. The common camshafts provided a valve toss speed well above the planned fuel cut-off rpm.

Increased cylinder pressures caused concerns for sealing the combustion chamber. A previous paper[1] described significant coolant aeration at higher power levels. A clamp load analysis found that the bolt loads required to resolve this were more than the current bolt could provide. Revising the bolt hardness to provide a tensile strength increase from 54kN to 60kN and modifying the thread configuration satisfied the requirements. New head gaskets were also required due to the cylinder pressure increase. A four-layer steel design gasket was specified.

LUBRICATION

During extended dynamometer testing at high boost levels and overspeed conditions, the level of aeration in the oil was higher than desired. A study of the impact of supercharger boost on oil drain-back and aeration found concerns with the standard method of determining whether the drain-back system was operating as designed. Table 3 compares the naturally aspirated condition (base), with the supercharged condition (boost). As noted, the aeration percentage is the same for the base and the supercharged engine, even though the oil level in the pan differs. This test was run at less than fuel cut-off engine speeds to prevent possible engine damage if the oil became excessively aerated. Aeration percentage did not always follow drops in oil levels, since there was still adequate oil in the pick-up. As engine speeds increased, the aeration more closely followed the oil level changes.

By measuring oil in the pan, we were able to design an improved windage tray. This tray was not considered mandatory for normal use, since the customer can not operate at the high boost levels and overspeed conditions used during development testing due to the engine protection strategies in the calibration. The tray does provide an extra level of protection for engines used under severe steady state operating conditions (such as dynamometer evaluation above the cut-off engine speed) as shown in Table 3.

	C'case Base	Pres. Boost	Oil in Base	Pan Boost	Aerat. Base	% Boost
GT Tray	-13.03	0	2.5	2	7.3	7.3
Alt. A	-2.27	-2.7	2	2	7.7	9
Alt. B	-13.65	-15.7	2.5	3	7.4	6.9
Alt. C	-3.14	-19.1	1.8	3.5	14.5	5.6

Table 3: Windage tray alternatives – performance results

ACCESSORY DRIVE

The accessory drive system had to be able to handle all the normal engine driven accessories as well as the increased loads from the supercharger. The supercharger loads were transferred to the engine structure through use of an external bearing support (Figure 6). The design was able to eliminate concerns about front main bearing and front bulkhead loads. The belt loads were managed, as shown in Table 4, through location of idlers and tensioners. The location of many of the engine driven accessories was limited by package space or the need to maintain common locations with the other engine offerings. A dual belt design as shown in Figure 7 allowed distribution of the accessory drive loads across the accessories and idlers.

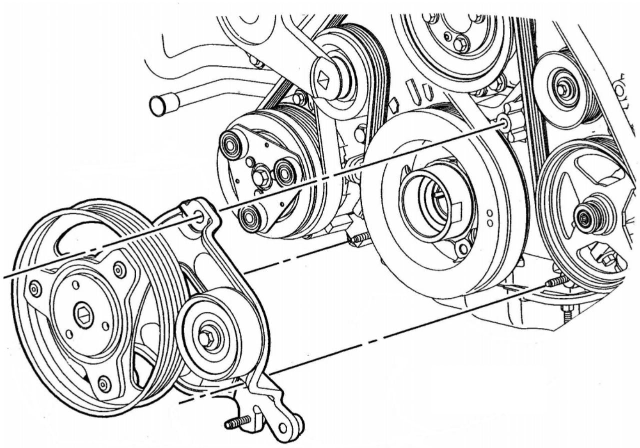

Figure 6. External bearing support

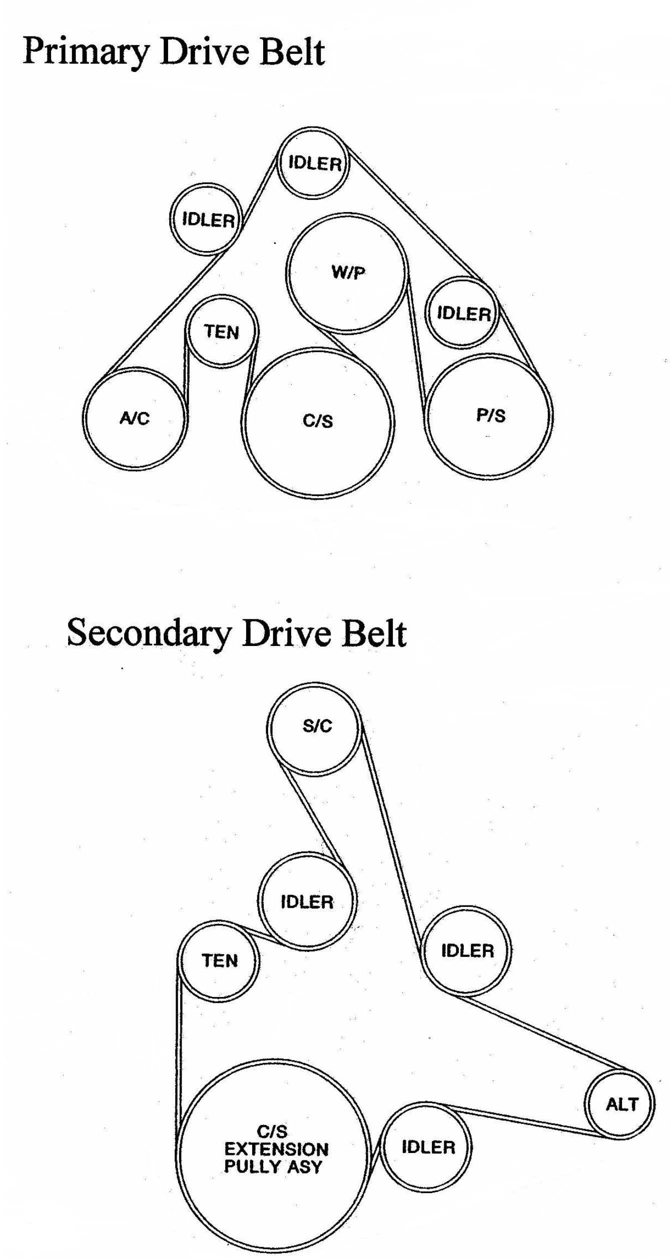

Figure 7. Accessory Drive pulley and belt layout

Component	Worst Load Newtons	% Time at Load
Primary Belt		
C/S	1465.3	0.01
P/S	1725.6	0.01
A/C	1171.7	0.01
W/P	705.5	0.01

Idler	886.1	0.01
Tensioner	491.5	100
Secondary Belt		
C/S	1089.9	0.01
Alt.	1514.2	0.1
S/C	1041.6	0.1
Idler	748.3	0.1
Tensioner	504.6	100

Table 4. Accessory loading conditions

VEHICLE EFFECTS

COOLING

Early vehicle testing showed a need for additional engine cooling for the higher output engine. The components sharing the package space available for cooling had to be sized, packaged, and developed to satisfy all the functional cooling requirements.

RADIATOR SELECTION

Additional cooling was required from the radiator due to the 22% increase in engine output. Table 5 shows some of the alternative evaluated in wind tunnel testing. Dimpling the base radiator tubes provided some of the required improvement. Major improvements were found by increasing the radiator tube size. Fin densities were also evaluated and optimized for both high speed and low speed cooling performance.

	Top Water	Oil	Water Pres.	Air Temp. Rise
	F	F	Psi.	F
26 mm	Base	Base	Base	Base
Dimple	-4.6	-4.5	2.8	11
36 mm	-11.2	-13.1	0	7.2

Table 5. Radiator effects. WOT Wind Tunnel at 150 miles per hour

OIL COOLER SELECTION

The radiator testing also indicated that additional cooling could be provided if the coolant flow rate could be increased. System analysis found that the oil cooler design provided the most opportunity for flow increase.

Redesigning the oil cooler for higher coolant flow produced the results shown below. The 4.6L 4-valve and supercharged 4.6L 4-valve oil cooler designs are shown in Figure 8. The new design improved the coolant flow path through the oil cooler, subsequently reducing coolant and oil temperature during high-speed engine operation.

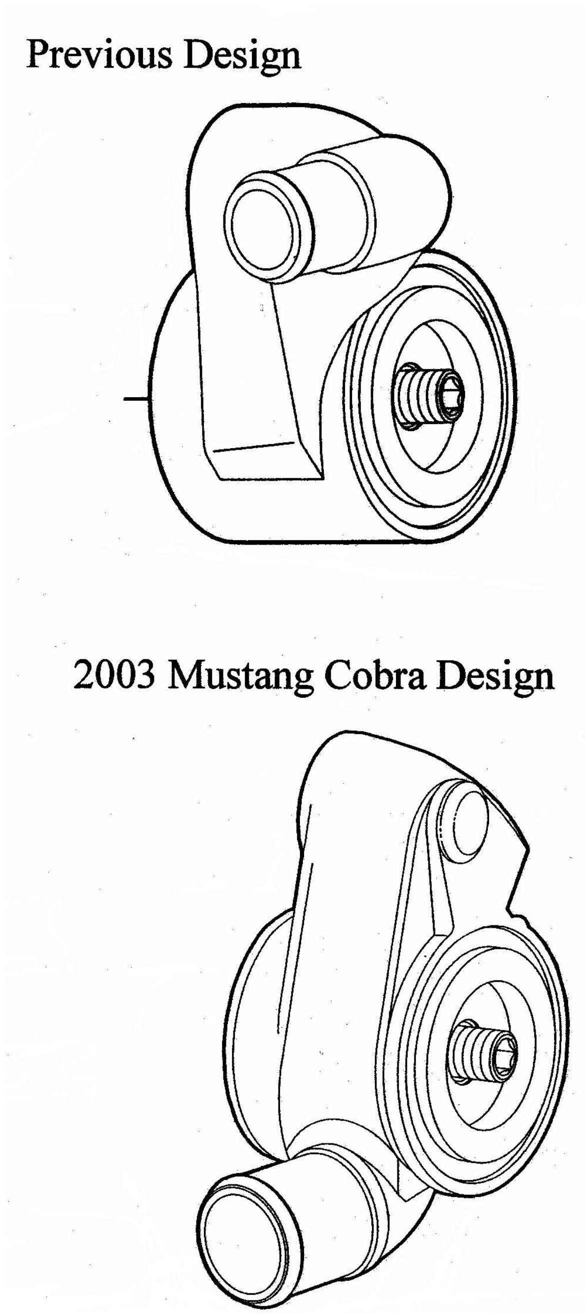

Figure 8. Oil Cooler design comparison

	Top Water Temp. F	Engine Oil Temp. F
Base	Base	Base
Previous	-0.7	-1.4
Selected	-5.1	-4.1
Alt. Cooler	-3.3	-3.5

Table 6. Oil Cooler effects. Wind tunnel at WOT, maximum speed

AERODYNAMIC INFLUENCES

Aerodynamic influences to the cooling system were also studied and improved. Front fascia openings were enlarged; slots were designed into the hood and tuned for optimum airflow, while air deflectors around the radiator were redesigned. The fin density of the intercooler radiator was also engineered, to increase critical airflow to the radiator, without compromising the vehicle's performance standards.

The combined influence of aerodynamic, radiator and oil cooler changes resulted in a vehicle that could be adequately cooled in city traffic or during high speed driving, even with the major increases in power.

EMISSIONS & FUEL ECONOMY

This vehicle meets all the emissions requirements in the countries in which it is sold. Fuel economy was substantially improved when compared to the historic muscle cars of the same power levels. The advertised power curve is shown in Figure 9.

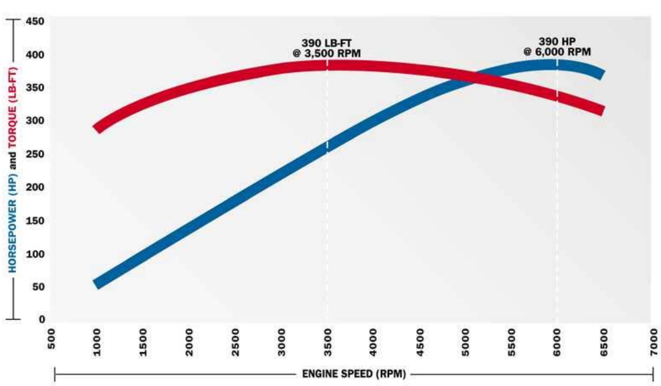

Figure 9. Advertised Power

ENGINE AND VEHICLE ASSEMBLY

The 4.6L Supercharged 4-valve per cylinder engine is hand assembled on the special, low volume “Niche Line” at Romeo Engine Plant. The Niche Line utilizes 20 teams, each with two assemblers, which follow an engine from bare machined block to finished, tested product. Hand assembly is accomplished via computerized transfer line with flexible engine pallets and positive accept torque guns to allow customization to several niche products while maintaining the quality of high volume production. Each engine assembly team follows their engine from start to finish, inspecting each component for quality along the way, and signing their names to the finished engine to show their pride and confidence in the product they have produced. An example of a “signature badge” signed by both assemblers is shown in Figure 10; a badge like this is affixed to the cam cover of each engine.

Figure 10. Engine signature badge

The vehicle is assembled on the regular production line intermixed with the other powertrains. The build process is developed through assembly designs, on-line prototype builds, and production intent builds. Each stage is critiqued by the participants as well as “fresh-eyes” reviews by non-participants. Production intent vehicles are validated through testing and inspection to provide optimum processes for the production builds.

CONCLUSION

The choice of supercharging over increased displacement to provide the low speed power desired for an authentic American muscle car resulted in substantial changes to the engine. The resulting product is assembled on existing engine and vehicle lines. All of the legislative, quality, reliability, and fuel economy requirements were met. The program to make and validate those changes in a short period of time required intense effort by the entire team.

The results met the requirements and provided the customer a powertrain that satisfied the image of a historic muscle car. Customer feedback through the 3MIS GQRS survey[8] shows satisfaction with overall engine operation six percentage points higher than the 4.6L 2-valve option. Power and pick-up results showed a 13 percentage point increase.

ACKNOWLEDGMENTS

John C. Thomson – Editor

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