Ford's new 4-Cylinder Engine Family

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Summary

The new gasoline engines in the new Ford Mondeo meet every expectation placed on a modern power unit. At the same time, the Duratec HE family represents the biggest engine program in the history of Ford Motor Company. Manufacturing capacities established for this engine will allow the production of up to two million units per year.

1 Introduction

With the model year 2001, and together with the new Mondeo, Ford will be introducing a completely new family of gasoline engines, called Duratec HE. In terms of the production volume, the development of this engine represents the biggest engine program in the history of Ford. Throughout Ford Motor Company, the Duratec HE will ultimately replace a total of eight different engine families. Design, development and manufacturing teams from Germany, England, Japan and the United States were involved in the design and development process. The early involvement of the purchasing department and suppliers was a basic prerequisite for realizing a simultaneous engineering process.

At the start of production, the engine will initially be built in two plants to be followed by worldwide production in five assembly plants with an installed capacity of over two million units per year. Although the various locations will focus on the production of certain engine types, each will have the capability of producing the entire range in order to ensure flexibility in responding to changing customer demands in the various markets. Currently, it is planned to use Duratec HE engines for more than 20 different vehicle applications.

In the new Ford Mondeo, the Duratec HE will initially be available with a displacement of 1.8L with 81 kW (110 hp) and 92 kW (125 hp) and a 2.0L version delivering 107kW (145 hp). Major development objectives of the new engine include:

- low specific fuel consumption
- design for a service life in excess of 240.000 km and at least 10 years
- balanced power and torque curves
- running smoothness and low noise emissions
- low maintenance costs through elongated service intervals and reduced service content
- light-weight design.

2 Engine Concept and Basic Dimensions

In Mondeo, the engine is installed in a transverse (east-west) direction, with the intake manifold located in front, in the direction of travel. Compared to the previous engine, and with regard to meeting future emission standards, engineers now have additional latitude for positioning the catalytic converter.

The engine is mounted at two points along the roll axis of the engine/transmission assembly. One of these mounts is located at the front end of the engine, while the other one is positioned at the transmission. A third bearing at the differential provides torque support.

The design of the basic engine allows the different variants to be operated with any fuel available throughout the world, like LPG, CNG and E22.

Figure 1 shows the longitudinal cross-section as well as a frontal view of the engine. The major technical specifications include:

- aluminium cylinder head with four valves per cylinder and integrated duct for exhaust gas recirculation
- valve actuation by mechanical bucket tappets, silent chain camshaft drive
- de-coupled aluminium valve cover
- stepped sinter-forged connecting rod with fracture split big end
- weight-optimised pistons with coated skirt and low top land width to reduce hydrocarbon emissions, and hard-anodised primary ring groove, equipped with three piston rings with optimized tangential load, to reduce friction
- cast crankshaft with four counter weights
- aluminium cylinder block with deep skirt, cast-in cylinder liners and bearing beam
- structural aluminium oil pan for stiffer connection of the transmission, resulting in increased natural or eigenfrequencies of the entire powertrain
- ancillaries directly mounted to the engine
- G-rotor-oil pump bolted to the cylinder block
- dual-mass flywheel for damping of torsional powertrain vibrations
- plastic intake manifold with high recycling content, vacuum-controlled charge motion control valves for improved mixture formation at part-load
- welded 4-in-1 steel-tube exhaust manifold
- electric thermostat to reduce friction by means of controlling water and oil temperature as required
- use of a fully incinerable oil filter insert.

The major engine specifications are summarized in **Table 1**.

3 Realisation of Quality Targets

To realize the specified service life of more than 240 000 km and a minimum of ten years, all of Ford's global quality databases, as well as external databases, were analyzed. The most common field problems identified in this research were then investigated for applicability to the Duratec HE engine.
The success of the design modifications made with components and assemblies concerned, including the materials and compounds selected, was verified in an extensive test program. For this, assembly components with unfavorable tolerances at the final end of the spectrum were tested under extremely severe ambient conditions and subjected to any kind of conceivable noise factor.

4 Description of the Base Engine

4.1 Cylinder Block and Oil Pan

Due to the specified objective of building a light-weight engine with high stiffness, the cylinder block, **Figure 2**, is made of a high grade, precision-sand-cast aluminium alloy. This manufacturing technology was selected because, due to higher directional hardening, it results in a composite of lower porosity, with high material exploitation. The design is characterized by a "closed-deck" cylinder head sealing surface and sidewalls lowered all the way down to the crankshaft main bearings. The oil gallery is pre-cast, requiring no machining. The same is true for the oil return passages, which have been pulled down all the way to the oil pan in order to prevent oil aeration.
The bearing beam made of aluminium, shown in **Figure 3**, and the ribbing of the cylinder block, optimized by means of FE-calculations, contribute to the minimization of radiated noise. Another important factor in the engineering design development was the stiff connection of the transmission to which the structural oil pan, shown in **Figure 4**, contributes significantly. All of these measures combined result in an increase of the first critical natural frequency of the power unit to above 300 Hz, which means that, due to the second order shaking forces, the vibrations inducted into the vehicle body via the engine and transmission mounts are minimal.

The grading of the crankshaft bearing shells is another measure primarily designed to enhance sound quality. From a total of seven different bearing shell classes, depending on the respective actual dimensions of the crankshaft journal and bore diameter, one of 13 different combinations of upper-and-lower bearing shell is respectively selected.

Like the Zetec-SE engine family [1] introduced in 1995, the new Duratec HE engine has cast-iron cylinder liners cast into the block. To reduce the volume of coolant, the water jacket has been lowered to about 70 percent of the stroke. This shortens the engine warm-up phase, resulting in better fuel economy and enhanced comfort because of a faster response of the heating system. The bearing pedestals have slanted bores to accommodate the oil injection nozzles for the piston cooling.

Other features of the cylinder block include an integrated water pump housing as well as a stabilizing chamber for crankcase ventilation, above which the knock sensor is bolted to the block.

In view of the selected engineering design, with long sidewalls and a bearing beam, with only 27.5kg, the cylinder block achieves a very competitive weight compared to other engines in the same displacement range. To minimize the total weight of the engine, the mounting points at the cylinder block were designed to enable ancillaries to be mounted without additional brackets. Compared to the use of mountings and brackets, this direct-bolting method provides the additional advantage of higher stiffness, which significantly increases the natural frequencies of the ancillary components. All ancillaries exceeded the target value for the lowest natural frequency, established at 500 Hz. **Figure 5** shows that the total weight of the engine defines new best-in-class values in the 1.8 to 2.0-litre displacement range.

4.2 Crankshaft Drive

Figure 6 shows the nodular cast-iron crankshaft. With only four counterweights, it contributes to the low weight of the engine. Regarding internal bending properties, bearing load and natural frequencies, this design does not have a disadvantage, compared to a crankshaft with eight counter-weights. The main bearings have a diameter of 52 mm, while the diameter of the big end bearings amounts to 47 mm.

The connecting rod shown in **Figure 7** together with the piston has a stepped design. It is sinter-forged in a process ensuring high dimensional precision and eliminating the need for weight classification of the connecting rods during assembly. Because of the advantages described in [2], the con rod big end is fracture split. The piston has a top land width of only 4.5 mm and a compression height of 28.5 mm. The piston skirt coating allows for smaller assembly tolerances to minimize piston noises, while reducing friction as well. The casehardened piston pin with a diameter of 21 mm has been offset by 0.8 mm toward the thrust side. The piston is equipped with the following piston rings:

- the first compression ring is a rectangular ring made of steel with nitrated flanks and a chrome-plated bearing surface. Because of the lapped bearing surfaces, the break-in period is significantly shortened
- the second compression ring is a stepped and tapered compression ring made of spheroidal graphite iron. At 1.2 mm the second compression ring has the same height as the first ring
- trisectional oil scraper ring with a total height of 2.5 mm and chrome-plated contact surfaces as well

The chrome-plating was used to minimize blow-by and oil consumption even after long engine service life. The wear characteristics of the first piston ring, analyzed by means of radioactive tracer measurement (RTM) and shown in **Figure 8**, confirm the effective wear protection provided by the chrome-plating. Compared to any other engine tested by now, the Duratec HE is at the lower end of the scatter band.

Because of the stringent NVH objectives established for the new engine, special attention was focused on the second order shaking forces when designing the cranktrain. Compared to the Zetec-E engines previously used in Mondeo, the amplitudes for both displacement variants could be reduced by more than 10 percent. In **Figure 9**, the second order shaking forces at 5000 rpm for the Duratec HE, compared to other engines, are plotted versus displacement. It is evident that the geometry of the cranktrain, combined with the weight-optimized design of the pistons, piston pins and connecting rod, results in best-in-class values for this displacement range.

4.3 Dual-mass Flywheel

Every engine of the Duratec HE range is equipped with a GAT dual-mass flywheel, **Figure 10**. This component, described in detail in [3] primarily enhances driving comfort at low engine speeds. Contrary to previous systems, torque is transmitted by a sextuple spring-wedge system installed on the circumference.

Together with the above-described engineering design measures to stiffen the cylinder block as well as the entire engine transmission assembly, this results in an extremely low level of radiated noise, **Figure 11**.

4.4 Cylinder Head

The four-valve cylinder head shown in **Figure 12** is made of a silicon aluminium alloy, using an SPM-low pressure manufacturing process, followed by thermal treatment to homogenize the material structure and to increase strength. The 29-degree-valve angle is the result of an asymmetric arrangement, with the exhaust valves inclined at 10 degrees to the cylinder axis. The bigger 19-degree-angle was chosen for the intake side because this enabled the use of bigger valves. The 10.8:1 compression ratio is designed for operating the engine with unleaded 95 RON fuel. To minimize the build-up of injected fuel on the ports, the injectors, instead of being installed in the intake pipe, have been installed in the head.

To reduce engine-out nitrogen oxide emissions and enhance fuel economy, the Duratec HE engines are equipped with an exhaust gas recirculation system. Via the EGR-duct cast into the cylinder head, and via a water-cooled EGR-valve, controlled by a stepper motor, **Figure 13**, the exhaust gas travels to the intake side from where it is centrally inducted into the plastic intake manifold via a short tube.

The cylinder head gasket is a two-and-a-half- layered steel design. The stopper layer has been laser-welded to one of the two functional layers made of high-grade stainless steel. The functional layers themselves are elastomer-coated for a better micro-sealing effect of the cylinder head and block surface structures.

The spark plugs used have copper-cored electrodes with platinum tips to increase the length of their working life.

4.5 Valve Train

The camshafts have five bearings and are made of chilled cast iron. The valves are actuated by mechanical bucket tappets. Contrary to previous Ford engine ranges, they do not have shims. Instead, they are graded and selected for proper fit during assembly. Like the intake valve, the exhaust valve is a mono-metal version. The valves are nitrogenated to obtain the required wear and seizing resistance, as the austenitic steel used cannot be induction hardened. Valve clearance does not require inspection during scheduled vehicle maintenance. This was achieved by the following measures:

- reduction of the actuating forces by a weight-optimized design of the components, for example, the tappets themselves as well as the valves, which have a shaft diameter of only 5.5 mm. The final turn of the valve springs has been retracted, which enables the use of smaller and lighter spring retainers, **Figure 14**. The tappets have a phosphate-coated surface, resulting in better adhesion of the lubricating oil and break-in characteristics
- optimization of the cam contours, using a simulation program for projections of the dynamic valve train characteristics, developed by Ford. This resulted in an optimization of the valve lift curve with regard to the contact force between the camshaft and the tappets as well as optimized valve-seating velocities
- use of specially selected materials for the valve seat inserts. The maintenance free operation of the valve-train specified by the design objectives placed considerable requirements upon the proper selection of the material to be used for the valve seat inserts located on the exhaust side. For this purpose, a special, accelerated test was developed, with a confirmed correlation to real-world driving modes at high engine speeds and component temperatures, for example, when driving on motorways. Ultimately, a sinter compound with a high molybdenum and nickel content was chosen, enhanced by a solid lubricating additive.

Wear tests and measurements performed on the tappets by means of radioactive tracer measurements, confirmed that the sum total of the single measures taken eliminated the need for checking valve clearance during the entire service life of the engine. The wear rate, shown in **Figure 15**, is extremely low within the entire engine speed range. The scatter band contains both engines with tappets and engines with roller finger followers. The wear characteristics shown refer to the contact surfaces of the tappet and the roller, respectively.

4.6 Camshaft Drive

The camshafts are actuated by a chain-drive requiring no maintenance. It consists of a tooth chain, which was given preference over a conventional roller chain due to its lower noise radiation. **Figure 16** shows the arrangement of the chain with a hydraulic tensioner on the slack side of the chain.

The selected engine mounting concept along the roll axis requires an engine mount at the front of the engine. This meant that, for assembly reasons, the chain case could not be integrated in the crankcase. The engine mounting bracket is an integral component of the front engine cover, **Figure 17**. Using this highly complex die-cast aluminium structural component as an example, **Figure 18** demonstrates how CAE tools were applied during development. This example compares the calculated surface velocities with the results of a holographic investigation in the original design iteration.

Because of the outstanding conformance of calculated and measured results, this model then enabled to determine the final design in just one further step. **Figure 19** shows the improved noise deflection achieved by optimized ribbing. The illustration represents the sound pressure level calculated in a plane at a distance of 0.5 meters from the engine.

4.7 Oil Circuit

The G-rotor oil pump, **Figure 20** is driven by a separate silent chain. The aluminium-alloy pump housing contains a pressure-relief valve to limit oil pressure. The pump lid contains a groove on the intake side connected to the delivery side in order to prevent air from being sucked in, in case of any leakage. For environmental reasons, the easy-change oil filter shown in **Figure 21** can be completely incinerated.

4.8 Coolant Circuit

The coolant circuit of the new Duratec HE engine has a longitudinal directional coolant flow with the water pump integrated in the cylinder block. A map controlled thermostat, **Figure 22**, with controlled by-pass circuit provides the proper degree of cooling as required. Inside the thermostat, there is an electrically heatable wax element, the basic design of which provides an increased thermostat opening temperature. Because higher temperatures lead to lower friction, this results in improved fuel economy at part-load. At high engine loads, the thermostat is under current and the coolant adjusted to a lower temperature level.

4.9 Sealing System

The oil pan and the front engine cover are sealed by a liquid sealant (RTV) applied in an automatic process. The application of the bead is monitored by a video camera connected to an image processing system. The rear crankshaft seal is delivered as a module. The actual PTFE-sealing element and the dust-protection lip are glued into the sheet metal retainer. The sealing of the engine block is also an integral component of this assembly. The front crankshaft seal -also made of PTFE with a dust-protection lip- comes pre-assembled in the front engine cover, **Figure 17**. The primary reason for using PTFE compounds is their high degree of reliability over a long service life as well as better chemical resistance to some of the substances found in modern synthetic engine oils. Elastomer-coated steel seals are predominantly used for static sealing applications.

4.10 Crankcase Ventilation

The design principle of the crankcase ventilation shown in **Figure 23** is a fresh-air system. From the oil separator bolted to the cylinder block with its integrated flow limiting valve a hose leads to the intake manifold.

In this manner blow-by gases are dispersed under partial-load operating conditions with the flow of fresh air sucked in across the valve cover. By venting the crankcase with fresh air, chemical aging of the lubricants is slowed down. At full load, blow-by gases are dissipated into the suction tract via the oil separator as well as the valve cover.

5 Engine Tuning

5.1 Intake System

The preliminary stage of the actual intake manifold design included calculations to investigate the following different concepts with regard to induction noise:

a) a conventional intake manifold with side entry plenum and minor differences in intake runner length due to vehicle package constraints
b) an intake manifold with a central throttle body and uniform intake runner lengths
c) an intake manifold with side entry plenum and varying intake runner lengths, resulting in an identical length between the throttle body and valve for all cylinders
d) an intake manifold with uniform intake runner lengths and identical length from the throttle valve to the intake runner

The investigations not only aimed to arrive at the optimal configuration with regard to the sound pressure level above the engine speed, but primarily served the purpose of optimizing the subjectively perceived sound quality with respect to roughness. For four-cylinder-engines, within the frequency spectrum, the amplitudes of the half and odd engine orders must be reduced versus the even engine orders. **Figure 24** shows the results obtained for configurations a) and d). The intake manifold with a central throttle body also resulted in a reduction of odd engine order levels, but only the ELT (Equal Length Tract) configuration d) ultimately produced the desired result of a complete separation of odd engine orders.

The intake manifold shown in **Figure 25** is a three shell friction-welded plastic component with a high recycling content. It shows the charge motion control valves located in the cylinder head flange, which, at part-load operation, are closed to intensify charge motion. When the flaps are closed, the remaining flow cross-section is reduced to about 25 percent of the total cross-section. The vacuum reservoir for the solenoid-controlled actuator is located between the intake runners of the second and third cylinders.

5.2 Exhaust System

The design of the exhaust manifold, **Figure 26**, comprises a welded steel-tube assembly, joined in a 4-in-1 configuration. By using the charge motion control valves, the engine can be operated in the early cold starting phase with extremely late ignition timing and resulting high exhaust gas temperatures. Although the vehicle has been homologated according to European Stage IV Emission legislation, there was no need for a close-coupled catalyst. Another factor, which contributes to this, is the clearly reduced heat capacity, compared to a cast exhaust manifold.

5.3 Torque and Power Characteristics

One of the design objectives for the new engine was to develop high low-end torque. When looking at the torque curves of the 1.8-l- and the 2.0-l-engines shown in **Figure 27**, it is clearly evident that a competitive result was achieved, even without the use of a variable intake system or variable valve timing. For comparison, the envelope of engines used in current production vehicles of this

displacement range is provided as well. The maximum torque of 170 Nm for the 1.8-l- and of 190 Nm for the 2.0-l-engines is reached at 4500 rpm.
Starting at 3000 rpm, the influence of the charge motion control valves on the curve of the full-load torque is felt, because, even when opened all the way, they provide a, though minor, flow resistance. At rated speed, the 2.0-l-engine experiences a deterioration of about 4.5 Nm or 0.3 bar. This disadvantage was accepted because of the advantages obtained at part load, described in the following sections.

5.4 Fuel Economy

The compression ratio, set at 10.8:1, represented a compromise between the specified high mean effective pressures on one hand and fuel economy objectives on the other. With optimized ignition timing, the results of 327 g/kWh for the 1.8-l-engine without EGR and 323 g/kWh for the 2.0-l-engine represent excellent values for the operating point of 1500 rpm, 2.62 bar used for a comparative analysis, **Figure 28**.
For the same operating point, **Figure 29** shows the correlation between the specific fuel consumption and the EGR-rate. With closed charge motion control valves, without the use of EGR, there is a slight disadvantage in consumption, due to higher pumping losses. While, with opened charge motion control valves, the minimum consumption is reached at an EGR-rate of 13 percent, the minimum is shifted to more than 20 percent when the valves are closed. Considering driveability under transient operation, the calibration was set to 16 percent for the operating point in question. Compared to the fuel economy of the Zetec-E engines used in the previous Mondeo [4], this results in an improvement of about 6 percent. The EGR- map of the 2.0-l-engine shown in **Figure 30** indicates that EGR is used in the lower to medium engine speed range, even at higher loads equating to 145Nm. This, in turn, results in the favorable brake specific fuel consumption map shown in **Figure 31**.
Combustion stability at idle speed is also positively influenced by the charge motion control valves. Despite the idle speed being lowered to 700 rpm, the standard deviation of the indicated mean effective pressure remains at very low values.
The brake specific fuel consumption shown in **Figure 31** was obtained on a tests bench under standard conditions and a coolant temperature of 90 degrees Celsius. In the vehicle, at part-load, there is further improvement resulting from the effects of the electric thermostat. **Figure 32** shows the influence of the electric thermostat on warm-up behavior during the NEDC-cycle. 310 seconds after the test has started, the conventional thermostat opens up at a coolant entrance temperature of about 80 degrees C, while the electric thermostat permits a further increase to over 100 degrees C. The increase in oil temperature noted in comparison with mechanical thermostats occurs with a certain time lag. The specific effects lowering fuel consumption include:

- lower frictional losses between piston and cylinder bore as a direct consequence of the increased coolant temperature and the resulting temperature increase of the lubricating film
- thermal de-throttling of the engine, i.e. an increase of manifold pressure caused by higher pressures of the intake charge at a constant volumetric efficiency
- reduced frictional losses in the oil pump and bearings because of increased oil temperature

Improved fuel economy under real-world operating conditions largely depends on the driving profile. With a warm engine operated in urban traffic conditions (ECE-cycle) the improvement amounts to about three to four percent. **Table 2** provides an overview of the fuel consumption in the new European driving cycle driving performance.

5.5 Exhaust Emissions

Figure 33 shows the cumulative exhaust emissions with reference to the limits established by European Stage IV emission legislation. Despite the decision not to use a close-coupled catalyst, the catalytic converter lights off within only about 70 seconds. The measured emissions were clearly below the specified design objective equating to 80 per cent of the EU Stage IV limits. These stricter target values for operating the vehicle with pre-aged catalytic converters were selected in order to ensure that the limits could still be met after 100 000 kilometers and catalytic converters having aged in the vehicle under highly adverse conditions.

The previously mentioned capability of the engine to increase the energy contained in the exhaust gas to heat up the catalytic converter by means of ignition retard after a cold start, is shown in **Figure 34**. Even with opened charge motion control valves, and with the standard deviation of the indicated mean effective pressure of 0.25 bar established as a limiting parameter, the engine already delivers a higher enthalpy flow during the warm-up phase than its predecessor. When the charge motion control valves are closed, the exhaust gas energy can be roughly doubled again.

6 Summary and Outlook

With the new Duratec HE, Ford is continuing its path of renewing its range of engines. Like the smaller Zetec-SE engine family, the new power unit has an aluminium cylinder block which, because of its stiff design and reduced second order shaking forces, provides excellent running smoothness. Outstanding fuel economy is achieved by minimising friction as well as the application of an exhaust gas recirculation system. The charge motion control valves enable the engine to be operated with high EGR-rates.

Other outstanding characteristics of this engine are its light weight design and long durability and service life. Minimal maintenance requirements were a central focus of attention, resulting, among others, in the use of a maintenance-free chain drive for the camshafts and maintenance-free valve tappets.

With the new Duratec HE engines, the new Mondeo already meets current European Stage IV emission legislation. The current low levels of raw emissions provide an excellent basis for ensuring that future standards, by taking additional measures, particularly in the area of exhaust gas treatment, will be met as well.

The sum total of its characteristics makes the Duratec HE a highly competitive product, providing a solid basis for further developments.

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