

Compact Engine Architecture for Best Fuel Efficiency and High Performance – Challenge or Contradiction

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ABSTRACT

The world of automotive engineering shows a clear direction for upcoming development trends. Stringent fleet average fuel consumption targets and CO₂ penalties as well as rising fuel prices and the consumer demand to lower operating costs increases the engineering efforts to optimize fuel economy. Passenger car engines have the benefit of higher degree of technology which can be utilized to reach the challenging targets. Variable valve timing, downsizing and turbo charging, direct gasoline injection, highly sophisticated operating strategies and even more electrification are already common technologies in the automotive industry but can not be directly carried over into a motorcycle application. The major differences like very small packaging space, higher rated speeds, higher power density in combination with lower production numbers and product costs do not allow implementation such high of degree of advanced technology into small-engine applications.

With these boundary conditions and the fact that the demand of lowering CO₂ emissions is also evident in the small engine market, solutions need to be created which are suitable for compact engine (CE) applications without major impact on the overall engine architecture. Therefore the development trend is focused on measures which can be easily implemented into existing engine design and powertrain packages optimizing:

- Mechanical efficiency
- Indicated efficiency

The mechanical efficiency improvement by reduction of friction is dependent on all interfaces with relative movement velocity. Type of bearings (roller bearings vs. plain bearings), surface conditions (type of coatings) and component specifications (piston ring pre-tension) are a few examples of deciding factors for friction reduction.

The major contributor in the indicated efficiency is the combustion. Especially high speed / high power motorcycle engines suffer very often from poor combustion stability and quality in part / low load operating condition which results in rich mixture ($\lambda < 1$) and therefore bad fuel economy. To increase the combustion quality residual gas content needs to be reduced and charge motion in the combustion chamber increased.

All these above described measures for reducing the CO₂ emission of a CE should be introduced into existing models without major changes in the design to have a quick and cost effective implementation into series production.

1. INTRODUCTION

In today's world we see a steadily growing demand for individual automotive transportation. Worldwide automobile production currently is at a level of approximately 70 Mio. units, motorcycle production over 40 Mio. units, both figures showing strong growth especially driven by Asian markets. To deal with this strongly increasing mobility on one hand and the need to save resources on the other hand, even higher efforts have to be spent to increase efficiency of all powertrain especially with internal combustion engines (ICE).

Among many potential measures for increasing efficiency and to reduce CO₂, some approaches focused on ICE-design are listed:

Friction

- Low friction bearings, cylinder/piston compound
- Light weight design
- Valvetrain, auxiliaries incl. crankshaft offset

Gas Exchange

- Port capacity / restrictions
- Charge motion

Combustion

- Compression ratio
- Combustion control

Energy Management

- Beltless engine (water-, oil-pump, etc.)
- Better warm up, improved cooling systems
- Electric recuperation, Start/Stop

Powertrain - Optimisation

- Downsizing, gear box technology, hybrid

Most of these measures are already implemented in large quantity production of passenger car powertrain. Due to optimized design and refined production processes, these components and design features become more and more into the focus of interest for motorcycles.

Complementary measures for reducing CO₂, such as reducing vehicle drag or alternative fuels, of course are very

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important measures for motorcycles, but are not considered in the content of this paper.

2. EFFICIENCY

The fuel consumption of a vehicle is beside other parameters like rolling resistance and aerodynamic resistance strongly dependent on the internal combustion engine and how efficient the energy of the fuel is converted into power on the output shaft and transmitted to the rear wheel.

In the first level, the efficiency of an ICE can be split up into the Mechanical Efficiency η_m and the Indicated (inner) Efficiency η_i . The mechanical efficiency is basically dependent on the mechanical losses and therefore resulting friction. In the indicated efficiency, all combustion related parameters like high pressure cycle, low pressure cycle and thermal efficiency are taken into account.

Optimization the overall fuel consumption of the ICE has to follow the main routes: optimization of all engine components in regard of friction as well as combustion measures especially in high performance applications, even where low load usage is more significant for every-day riding.

2.1 MECHANICAL EFFICIENCY

The relation between engine friction reduction and fuel consumption is shown in Figure 1. For a typical powertrain a 10% friction reduction on the engine results approximately in a 2-3% benefit in the cycle fuel consumption.

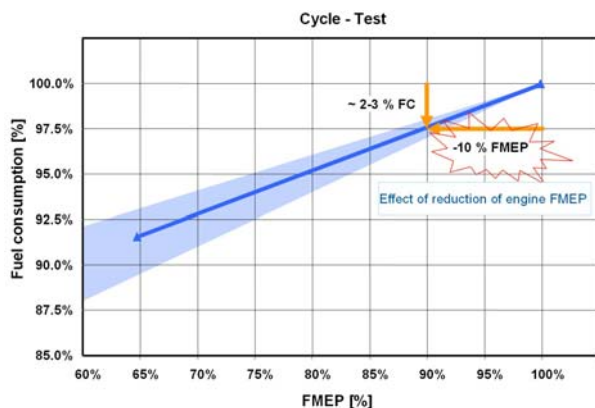


Figure 1: Engine Friction versus fuel consumption [1]

The main potential comes from improved utilization of the fuel energy through reduction of base engine friction, management of the water and oil pumps, and finally energy management measures such as start-stop and recuperation.

Figure 2 shows the relative benefits of these measures based on a 4 cylinder gasoline engine in a current passenger car application.

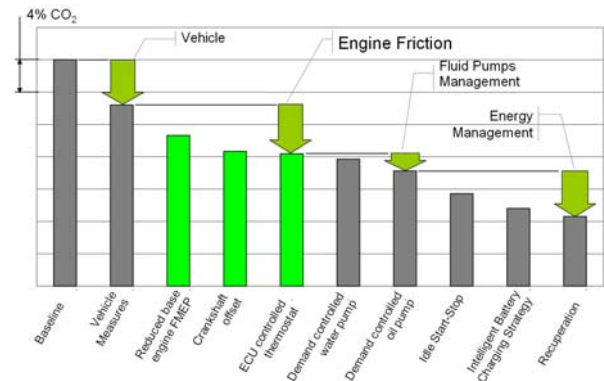


Figure 2: Relative effects of base engine friction and thermal management measures in automotive applications [1]

Although this comparison is based on a passenger car powertrain, each component could be transferred into a CE application with a similar benefit.

Base Engine Friction

The base engine friction is influenced both by the overall engine architecture and the detailed optimization of the affected systems and components.

The main sources of base engine friction are well known from strip-down measurements from a wide range of engines. The largest contributor is the piston to bore interface (piston, ring and liner), which contributes more than one third (35%) of total friction. The next largest are crankshaft main and crankpin bearings. The effect of valvetrain and timing drive friction also can be significant, depending on the choice of valvetrain system.

Figure 3 shows the overall friction contribution as an example for a 4 cylinder inline motorcycle engine.

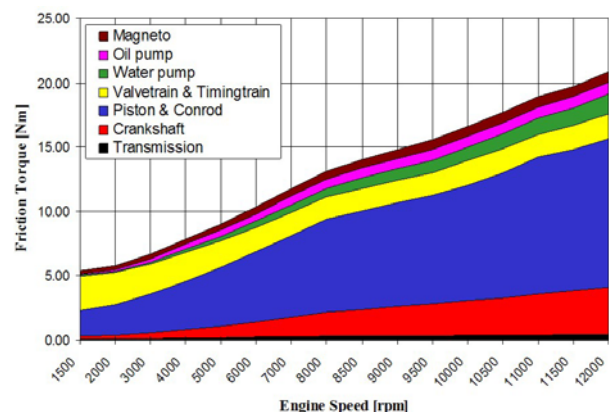


Figure 3: Friction Torque Contribution [2]

Figure 4 shows the relative contribution of each assembly group for this example. A clear trend can be seen showing the three major contributors. The maximum losses are caused by piston and conrod with around 50% of share (combined contribution of piston& rings and conrod).

big&small end). Valve train & timing drive 20% and crankshaft do contribute around 12% of the engine friction, with the valve train & timing drive showing a higher share at lower engine speeds whereas the crankshaft losses rise with higher revolutions.

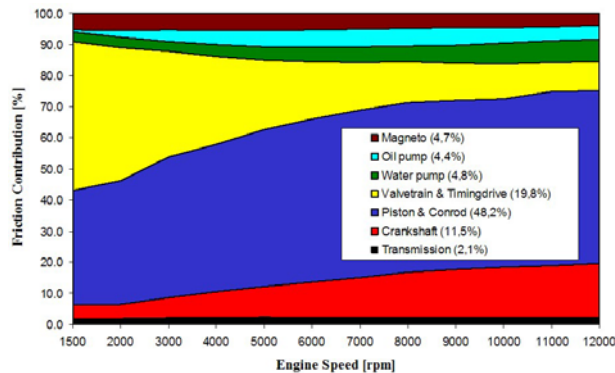


Figure 4: Relative Friction Contribution [2]

The biggest reductions in base engine friction are therefore to be found when considering these systems in detail.

Fluid Pumps Management

Coolant and Lubrication pumps consume a significant amount of driving power. Since the size of the pumps is based on the worst-case operating conditions (full load), the pumps are typically oversized for all other operating points, and therefore waste energy at low load operation. This parasitic loss can be reduced by utilizing pumps which operate on-demand.

Energy Management

Measures in this area include idle start-stop, and improved (intelligent) control of the battery charging to reduce the energy consumed by driving the alternator. In a further step, kinetic energy of the vehicle can be recovered and converted to electrical energy in the battery, by charging the battery during vehicle deceleration.

2.1.1 LOW FRICTION ENGINE CONCEPT APPROACH

In the following, design optimization of engine architecture with regard to base engine friction will be discussed in detail.

Number of Cylinders

Thermodynamically a cylinder capacity of 500cc would be ideal, however the specific demands of different two wheeler applications finally determine the number of cylinders. For a high performance motorcycle engine the choice is towards much smaller cylinder capacity, typically a 250cc cylinder capacity configuration, allowing high engine speeds for extremely high specific power.

Bore and Stroke

The force due to the gas pressure in the cylinder increases with bigger cylinder bore; as a result the dimensions of the crankshaft bearings increase with bore diameter. However, a longer stroke leads to a higher average piston speed, which also tends to increase friction. For typical cylinder sizes with moderate rated speed, the effects practically equalize one another, and the choice of bore and stroke can be made based on other considerations than friction, such as combustion chamber shape or packaging.

In high performance CE high speeds result from higher rated speeds needed to achieve high power density without charging, therefore the choice of Bore:Stroke is driven purely by performance and not by fuel consumption.

Crankshaft offset

A crankshaft offset is introduced to reduce the normal forces between piston and liner and thereby reduce the friction in this interface. The influence on the friction changes with engine speed and load and therefore the optimum amount of offset depends on the engine operating range in a specific application. Figure 5 shows the calculated reduction of piston-liner friction with increasing crankshaft offset, for different values of piston pin offset at 1700rpm. Since the friction reduction levels off at offsets above about 8mm this value was selected.

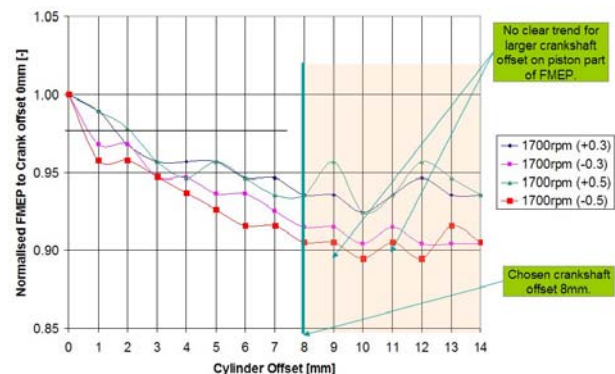


Figure 5: influence of crankshaft offset on piston-liner friction at 1700 rpm [3]

2.1.2 LAYOUT OF MAIN COMPONENTS WITH LOW FRICTION FOCUS

Cylinder block

The Cylinder Block is typically designed based on requirements for durability and NVH. Relevant for the friction behavior are the main bearing bores and the cylinder bores, as these are the interfaces to the moving cranktrain components.

Bottom End Concept, Main Bearing Clearance and Alignment

Aluminium typically is selected as the material for the crankcase, based on its low mass and high thermal conductivity. Design concepts are developed to achieve optimized strength and stiffness. Due to the low elastic modulus of the material, closed crankcase structures need to be applied, with consequent reduction of the cylinder block mass, while achieving good overall powertrain stiffness.



Figure 6: cylinder block structure: Aluminum low pressure casting with fracture split main bearing inserts [4]

Using aluminum, cast-iron main bearing inserts can be cast integrally with the cylinder block and separated by fracturing. Thus a precise location of the cap is possible (with the benefits of a consistent bearing clearance, leading to lower friction and oil flow rates at the main bearings) while reducing machining operations. In contrast to a pure aluminum block structure, which suffers due to the differential thermal expansion of crankshaft and block material, the main bearing clearance is nearly constant over the engine speed range. Therefore the oil demand is lower than for the pure aluminum block, Figure 7.

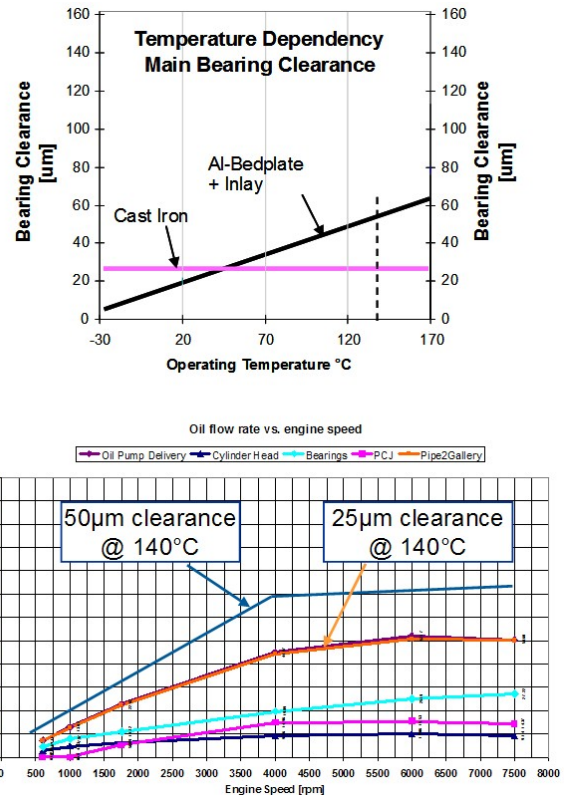


Figure 7: Main bearing clearance and oil flow demand for different cylinder block materials [1]

Bore Distortion, Honing

Dependent from high firing pressure, high cylinder head bolt forces are required to guarantee sealing of the cylinder head gasket. To support the gasket function, a closed-deck design usually is selected for high performance versions. A cooling bore between the cylinders is applied for very high ratings to limit the temperature between the liners.

The head bolt forces tend to increase the distortion of the cylinder bore, especially the 4th order. A low magnitude of distortion is an important prerequisite for achieving a piston ring pack design with low friction as well as good oil consumption and low blowby values. Therefore particular attention is paid to the design of the cylinder block for minimizing distortion. In addition to optimize the overall stiffness of the structure, several specific design features are included, Figure 8. The structural design is optimized by means of FE simulation to obtain benchmark values of bore distortion, Figure 9.