

CO₂ Reduction Potential through Improved Mechanical Efficiency of the Internal Combustion Engine: Technology Survey and Cost-Benefit Analysis

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ABSTRACT

The need for significant reduction of fuel consumption and CO₂ emissions has become the major driver for development of new vehicle powertrains today. For the medium term, the majority of new vehicles will retain an internal combustion engine (ICE) in some form. The ICE may be the sole prime mover, part of a hybrid powertrain or even a range extender; in every case potential still exists for improvement in mechanical efficiency of the engine itself, through reduction of friction and of parasitic losses for auxiliary components.

A comprehensive approach to mechanical efficiency starts with an analysis of the main contributions to engine friction, based on a measurement database of a wide range of production engines. Thus the areas with the highest potential for improvement are identified.

For each area, different measures for friction reduction may be applicable with differing benefits. The proposed measures may be cost intensive, such as the addition of low friction coatings, or variable-capacity pumps, whereas others such as the optimization of cylinder bore distortion or coolant pressure drop by design measures have zero add-on cost. Some are concept level decisions only applicable to a new engine design; others can be implemented without significant investment even for an existing engine design.

In this paper the major potential improvements to mechanical efficiency of the internal combustion engine are identified for each engine system. The improvements are ranked in terms of friction benefit and impact on product cost.

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INTRODUCTION

The need for significant reduction of fuel consumption and CO₂ emissions has become the major driver for development of new vehicle powertrains today, forced by a combination of legislation [1, 2] and pressure from consumers due to fuel price increases. This has led to a wide range of new hybrid powertrain concepts, combining electrification and advanced control systems to maximize the utilization of the input energy in the fuel. With the exception of pure electric vehicles, which will remain a niche product until a significant improvement in battery technology enables realistic ratios of driving range to cost, all these concepts retain an internal combustion engine in some form, and this is expected to remain the case for the foreseeable future [3].

Hybrid concepts of all types seek to improve the overall system efficiency by recovering energy lost during

deceleration and by shifting the operating point (speed and load) of the ICE to a more efficient part of its operating range.

For conventional powertrains, downsizing and downspeeding are also approaches to utilize the ICE more efficiently by adjusting the matching of engine, transmission and vehicle.

Whether the ICE is the sole prime mover, part of a hybrid powertrain - or even a pure range extender - potential remains for the improvement of mechanical efficiency of the engine itself, through reduction of friction and of parasitic losses for driving auxiliary components. Continued efforts to optimize the ICE remain therefore an essential part of the industry's efforts to fulfill future requirements on the automotive powertrain.

Figure 1 shows the energy distribution for a typical vehicle in the New European Driving Cycle (NEDC), which is used to determine the official values of fuel consumption and CO₂ emissions in Europe. On the right hand side are the losses from the transmission and drive line as well as the parasitic losses from electrical systems and engine auxiliaries. On the left are the heat losses, resulting mainly from the basic thermodynamic efficiency of the engine cycle, but also in part from frictional losses which convert energy to heat which mainly transfers to the engine oil and hence to coolant. The importance of adopting measures on the vehicle to reduce rolling and air resistance as well as mass can be clearly seen - 20-25% of the fuel energy in this area translates to 7-9% which is converted to kinetic energy of the vehicle.

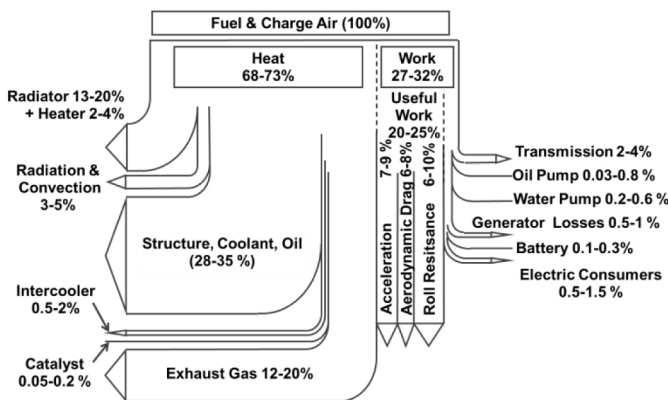


Figure 1. Energy Flow in the European Certification Cycle (NEDC)

For a particular powertrain and vehicle configuration, different improvement measures may be feasible. Figure 2 illustrates for one completed development the realized reductions through vehicle measures, thermal management and base engine friction reduction. In this example, mechanical friction reduction of the base 1.5l diesel engine and demand-controlled fluid pumps together achieved close to half the total CO₂ reduction, confirming their high potential in the context of overall powertrain efficiency optimization and CO₂ emissions reduction.

All interfaces with relative motion between the engine components contribute to friction to some degree. A comprehensive approach to friction reduction starts with an analysis of the main contributions to engine friction, based on a measurement database of a wide range of production engines. Thus the friction generating interfaces can be ranked in terms of friction contribution to identify the areas of highest potential reduction.

For each area, different measures for friction reduction may be applicable, such as macro-geometry modification (e.g. bearing diameter), micro-geometry (e.g. bearing roundness and alignment) or other parameters (e.g. forces or relative velocity).

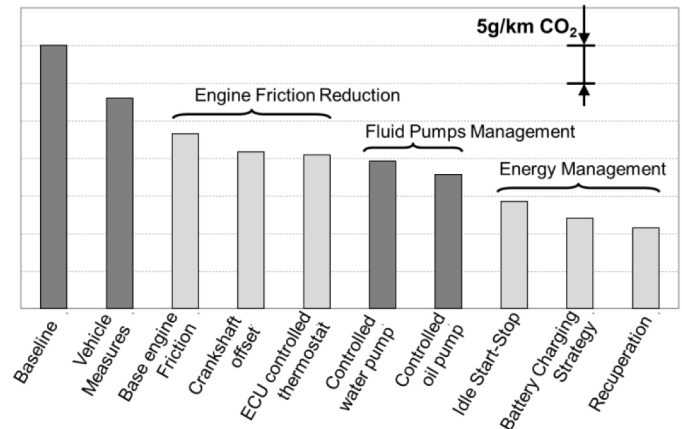


Figure 2. CO₂ Potential of Engine Mechanical Efficiency relative to vehicle and energy management measures (NEDC)

The proposed measures may be cost intensive, such as the addition of low-friction coatings, or variable-capacity pumps, whereas others such as the optimization of cylinder bore distortion or coolant pressure drop by design measures have zero on-cost. Some are concept-level decisions only applicable to a new engine design; others can be implemented without significant investment even for an existing engine design.

In this paper the major potential mechanical efficiency improvements on the internal combustion engine are identified, system by system. The improvements are ranked in terms of friction benefit and cost of implementation.

SOURCES OF MECHANICAL LOSSES IN THE INTERNAL COMBUSTION ENGINE

Engine mechanical losses - whether due to friction or to parasitic losses e.g. mechanical drive of the oil pump are generally expressed in terms of Friction Mean Effective Pressure (FMEP = IMEP - BMEP) and given in the units *bar*. Thus friction values can be compared between engines of different capacities.

Figure 3 illustrates a scatter band of engine FMEP against engine speed for passenger car engines, based on the database of engine measurements performed at AVL. The generally higher friction level of Diesel engines is primarily due to the higher cylinder pressures which require larger crankshaft and conrod bearings, and higher piston ring forces for gas sealing. Notable however is that the best diesel engines have lower FMEP than a significant proportion of gasoline engines. This is an indication of the sensitivity of friction to the design and technologies applied.

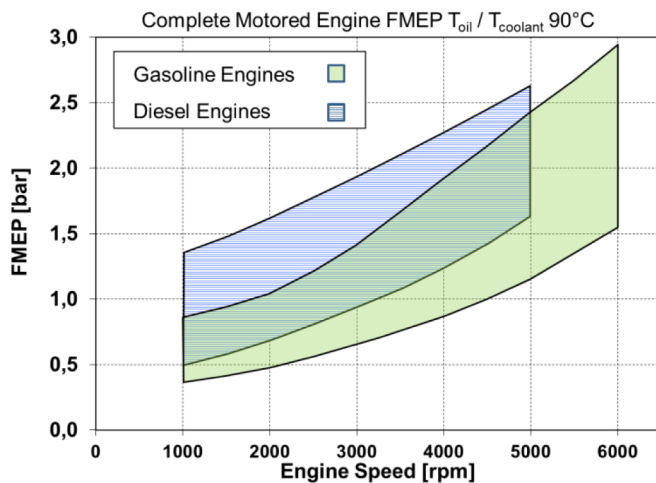


Figure 3. Engine FMEP Scatter band: Motored Engine Measurement - Inline 4 Cylinder Engines <0.6L/cyl

The FMEP is measured by motoring the engine (i.e. without combustion) with oil and coolant conditioned externally to 90°C. This method is chosen for its simplicity and repeatability. Measurement of friction of a fired engine is possible but requires significantly more preparation due to the high accuracy of cylinder pressure indication required. Since the correlation between motored and fired engine friction is good (based on a smaller sample of engines which have been tested using both methods), the motored friction is considered a sound basis for comparing different engines.

Furthermore, fired engine friction can by definition only be measured on a complete engine, making it impossible to obtain any information about the friction contributions of the individual engine subsystems. The ability to break down the total engine friction to identify the main friction sources for a particular engine and compare it to other benchmark engines makes the strip-down test method a very useful tool.

Engine Friction Contributions Based on Strip-Down Testing

In the strip-down testing method, the motored FMEP of the complete engine is first measured. The engine is then progressively disassembled, system by system, with intermediate measurement of motored FMEP of the remaining engine assembly at each step. Thus the overall FMEP can be broken down to the main engine systems. Figure 4 shows a typical result for a 2.0L passenger car diesel engine.

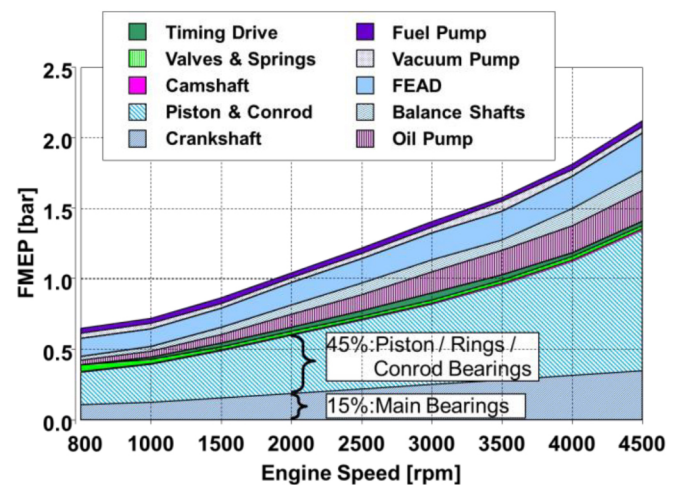


Figure 4. Engine FMEP Breakdown to Systems: Strip-down Measurement

It is apparent that for this example the most significant contributions to engine friction are:

1. piston - bore interface including rings + conrod bearings (~45%)
2. crankshaft main bearings (~15%)
3. 2nd Order mass balancer shaft system
4. valvetrain and timing drive

Additionally parasitic losses for driving auxiliaries and engine oil and water pumps are a significant contribution:

1. belt-driven auxiliaries incl. water pump
2. oil pump
3. fuel and vacuum pumps

Based on the measured distributions of a wide range of engines it is possible to establish a benchmark or typical range for FMEP for each system. For a specific existing engine, a comparison of the actual strip-down measurement can be made with the benchmark for each individual system, and thereby more information about the strengths and weaknesses of a particular engine configuration can be obtained. In more general terms this knowledge can also form the basis for identifying areas of research and development for new friction reduction measures and technologies.

Friction Target Setting during Product Definition

The database of engine strip-down results allows comparative data to be generated for different engine concept design options. This information about the relative frictional performance of individual system solutions can be used to influence the design and technology choices during the concept design stage. One example, shown in figure 5, is a

comparison between direct- (crankshaft-) driven oil pump and an indirect drive method such as chain.

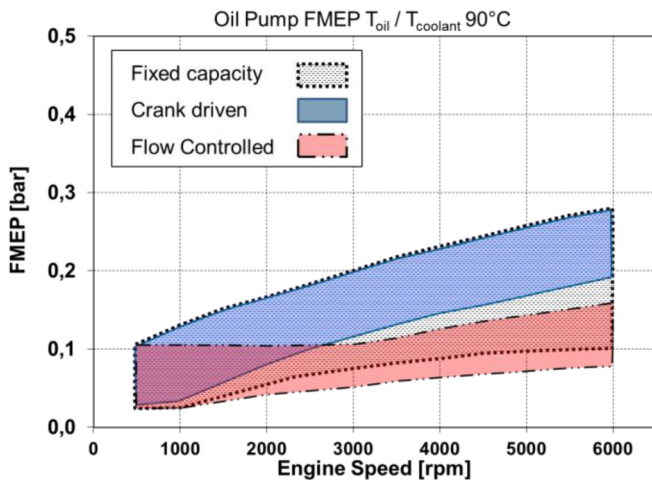


Figure 5. System level FMEP benchmark: Oil Pump - Flow controlled vs. Fixed capacity Crank- or Chain-driven

Simultaneously, by quantifying the expected friction range for the chosen concepts at system level, an engine friction target can be built up in a bottom-up approach early in the product definition phase. This can be compared with the top-down requirements for total engine FMEP based on the engine level fuel consumption targets (BSFC at selected operating points).

This early assessment is an important check to confirm that the chosen engine technologies are in line with engine level targets and to adjust the targets - or technologies - if needed. This is essential since challenging friction targets naturally tend to conflict with the fulfillment of other targets such as NVH, weight or cost targets.

Friction Prediction and Tracking during Product Development

The system-level breakdown of targets can be used to monitor the overall friction level during the complete product development. Thus the effect of new inputs for example from component suppliers or engine manufacturing plant can be evaluated for possible effects on the engine friction targets, prior to decision.

As the product definition is refined, inputs from CAE-Simulation and later from rig testing can be substituted for the benchmark-based data for individual systems. Finally the strip-down testing of a complete prototype engine confirms the predictions or identifies areas where further development is required. Figure 6 shows a process flow chart for the friction prediction and tracking process, where during the development time the methods for the prediction is adjusted to the available design status.

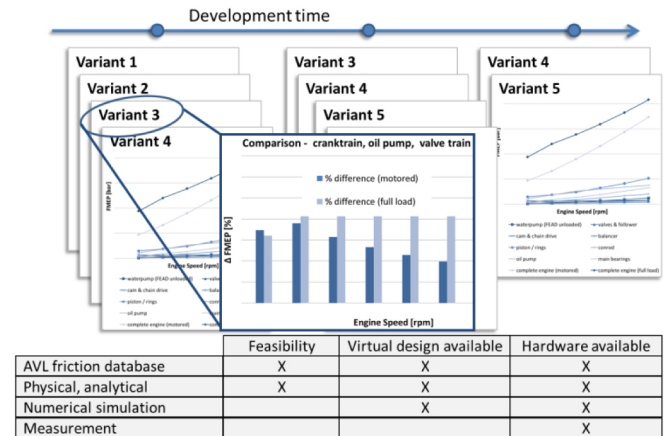


Figure 6. Friction prediction and target tracking during product development

Taking the crankshaft bearing system as an example, the contribution of a similar engine from the benchmark database is taken as a starting point at the start of the development. The impact of different design variants with adjusted bearing diameters on the overall friction contribution can be derived from simplified physical models. To increase the accuracy of the friction prediction, numerical simulations are used for design variants after the initial virtual design model is available. For the crankshaft, a multi-body simulation with coupled elasto-hydrodynamic (EHD) bearing simulation is performed, taking into account the selected oil type and temperature, detailed bearing design including micro-geometries like barreling or initial wear during run-in, and the stiffnesses of crankshaft and crankcase. These results confirm the durability of the crankshaft bearings as well as providing a more refined calculation of the bearing friction.

COUNTERMEASURES

Based on the strip-down data, the main subsystems influencing the engine's mechanical losses have been identified. Now each subsystem can be evaluated in more detail and the main parameters influencing the losses, and hence the improvement potentials, described in detail.

Piston-Bore Interface

The piston-bore interface is the main contributor, with almost 40% of the total engine friction. This is inherent in the nature of the interface, with reciprocating motion and therefore mixed friction at the low velocity regions close to TDC and BDC, as well as high normal loads between the friction partners piston and liner due to the reaction to the connecting rod axial force. Furthermore the piston rings, in order to seal effectively against oil and combustion gases, have to push actively against the liner.

Friction countermeasures in this area address these facts in several ways.