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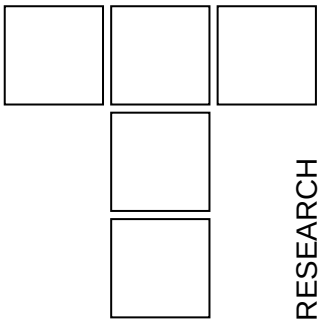

Methods of Tribological Improves and Testing of Piston Engines, Compressors and Pumps

With a large numbers of reciprocating internal combustion engines, compressors and piston pumps in service, even the smallest improvements in tribological efficiency and durability can have a major effect on the world fuel economy and the environment in a long-term.
The cylinder system constitutes the most critical part of the combustion engine, compressors and piston pump. In this role, the system accounts for a large portion of total machinery friction, which illustrates the importance of a well engineered power cylinder assembly.
The increase in specific performance of gasoline and diesel engines – and all piston machinery- is accompanied by a need for economical fuel consumption requiring, for instance, a reduction in cylinders-pistons friction.
Validation ensures that the system dynamics work together as a whole: the tribological interface of the piston rings and cylinder liner; the gas dynamical system of the piston rings as well as the piston and power transmission system of the piston, piston pin and connecting rod.
The implementation of complex tribological methods and the challenge to use these tools to shape the piston engines, compressors and pumps will help the future possibly herald the most significant and exciting phase in the evolution of vehicle manufacturing.

Keywords: *efficiency, IC motor, piston compressor, piston pump, tribological testing*

Reduction of development periods and constant increase in demands for quality of products has led to implementation of test vectors, Figure 1, directly according to contents of development transactions. In its nature, it is a crossover from static to dynamic contents during the development period, thus it is named with vectors. Global algorithms must be active in all procedures (*"In the loop"*).

Let us begin with an imaginary model. It is followed by software, therefore with virtual content described by theoretical quantities. Then a physical prototype follows, that is hardware and a sum of cognitions gained by tests on samples. All experiences and suggestions from dynamically defined "Hardware" are being taken over by "Models" and "Software" in their loops (*"In the Loop"*) as inputs generated after multiple optimizations. Throughout their whole lifetime, product characteristics are flowing to these creative phases with simultaneous support of more and more perfect models and complex test procedures.

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Test results make a database and, then, engineer's knowledge base converges before determination of valid decisions. Both phases are the segments of the most organized system of total quality control (*TQC*). It is a national and international criterion for ecologically acceptable industrial production.

When fuels and lubricants are in question, EU regulations and the American tradition are fully accepted. Since, these are the objective conditions for qualification of the researchers, the measuring technique and the products, there is an EU regulation on compatibility of laboratories and researchers working on these transactions. Formerly, it was inconceivable to standardize total number of objections for complex products consisting of several thousands of parts. Now, it is already obvious, that only those OEM-s with 1% upper limit for errors (beyond 2005), can survive in vehicle production, Figure 2.

The usual tests with marginal costs are listed in Table 1. Products descriptions begin with their physical-chemical characteristics followed by reviews of their behavior on standard laboratory devices.

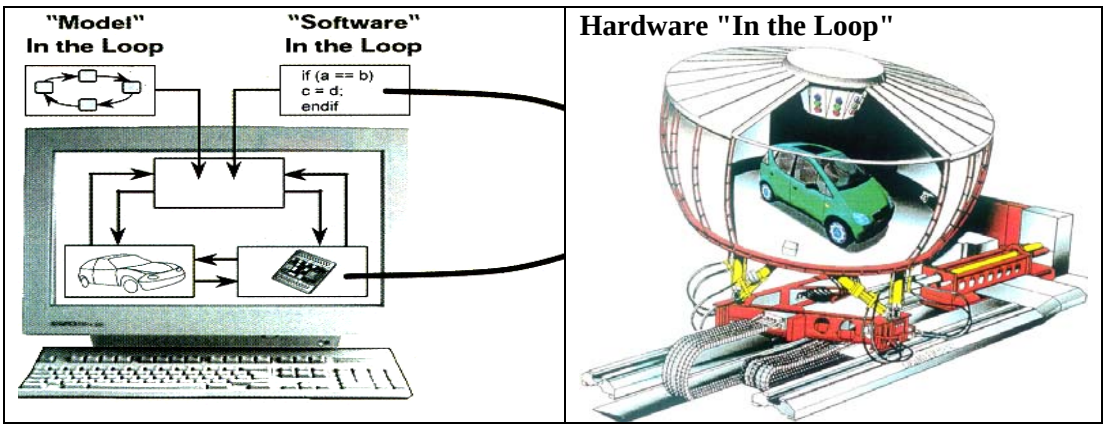


Figure 1: Dynamic active development systematic

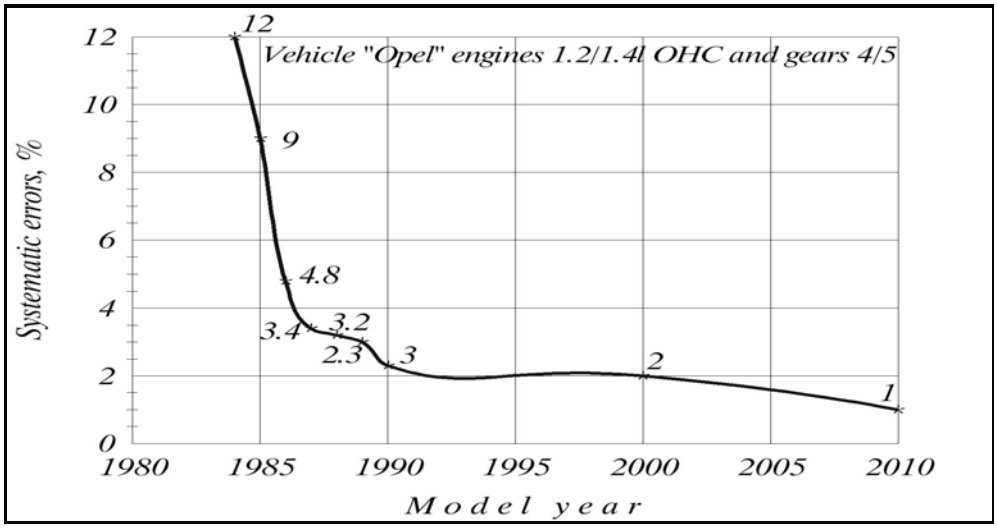


Figure 2: Productions errors limits for years (Vehicle "Opel")

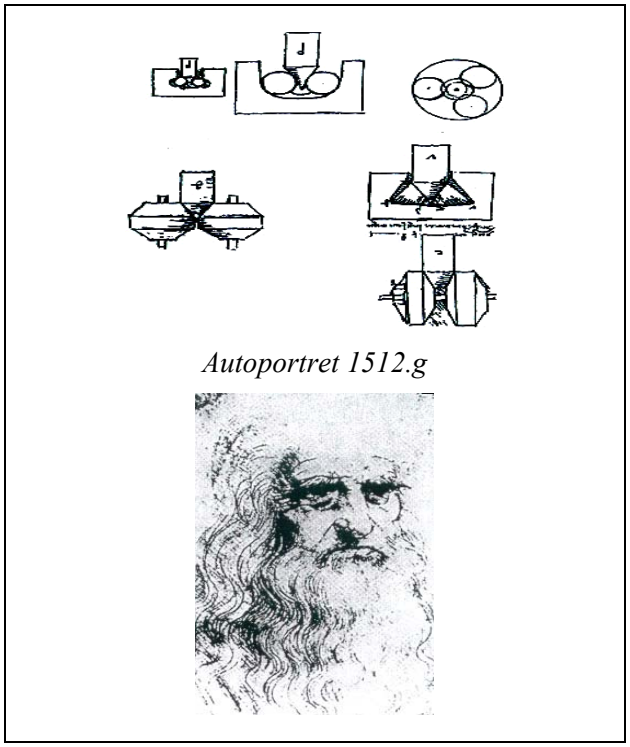
Table 1: Different installation, equipment, instrumentation and test cost

Analytical measurement	Laboratory equipment	Dynamometer testing	Service trials
Physically & Chemically properties: • Viscosity • Vaporization • Distillation	Standard: • Four -balls machine • Cam/tapped • Timken • Tribometers...	Cool & Hot: • FZG ring • Sequences • Tests engines	Bench tests: • ECE, FTP, Japan etc. Road tests: • In use...
ADVANTAGES:			
• Repeatability	• Reproducibility	• Test variability	• Final rating
DURATION:			
• Hours	• Daily	• Weeks	• Months
COST:			
50 - 500 $	500 - 5.000 $	15.000 - 40.000 $	~400.000 $

Laboratory devices are relatively simple machines on which applicative qualification of new solutions of all machine materials and fuels and lubricants purpose can be made. In second step, extension of areas on which objective suggestions for their behavior are wanted, is done by modification of a "standard" device. For the area of lubricants, entire sets of tribometers and numerous modifications of standard laboratory devices exist today. The following tests have the broadest application and long standing verification, Table 2.

Table 2: ASTM lists and descriptions of special tools, instruments and sample preparation

Lubricants	***ASTM D***	Properties	***Equipment***
Dry-Film Lubricant	2981	• Lubricity • Shear • Wear	Tribometer "block & disk"
Synthetic origin	2266		Four -ball machine
Mineral oil **base**	4172		Four -ball machine
Hydraulic oil	2882		Hydraulic pumps



Autoportret 1512.g

Figure 3a: Layout from "CODEX MADRID I" Leonardo Da Vinci (1452. – 1519.)

There are many suggestions in the papers of L. Da Vinci, one of the first designers of complex machines, Figure 3. Later, each device was named after its designer or producer: ***Timken***, ***Falex***, ***Amsler***, etc. The ***Almen-Viland*** principle is the bearing-spindle assembly (***A***), Figure 3b. In ***Timken*** machine, there is a contact between the rotating disc (full circular ring) and inner silent block (***B***).

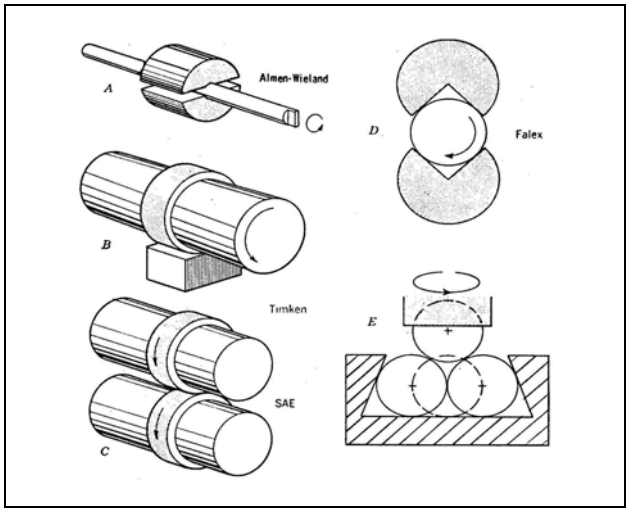


Figure 3b: The actuality tribometers

The disc has a role of a spindle, while the wear marks are measured on the silent block that is the critical element of this tribological couple.

Verifications of components and systems built as modules in motor vehicles are higher and, at the same time, phases that are more expensive. Final verification on vehicles refers to verification of function, application behavior and endurance, Figure 3c.

Development of new machines means the application of nano-technologies and new materials. Therefore, timely preparations for new adequate methods should be conducted in analysis. Let us only mention composites, solid lubricants, ceramics and fullerenes.

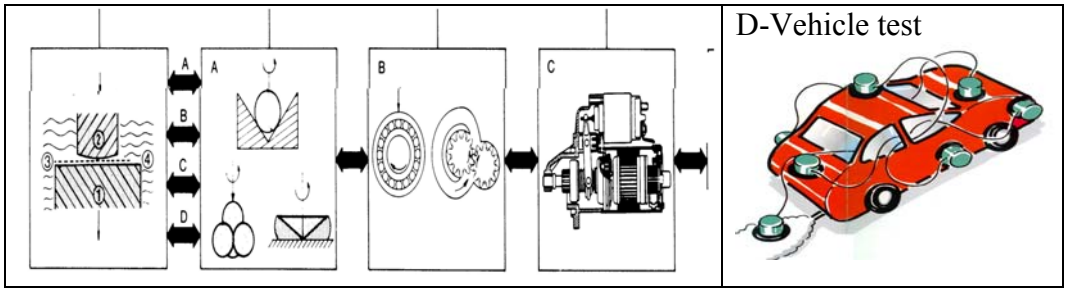


Figure 3c: Steps of modeling in use compliance testing
A) Smart modeling B) Dominant term C) Part behaviour D)Test of systems

Miniaturization means that lighter and smaller devices that have their own mobile variants are to be expected in future. Logistic support relies on demand to ensure on-site calibration and maintenance. Formula 1 experiences, where mobile mini-laboratories with intelligent sensors have already taken the role of flexible service systems, are taken as models for such activities in vehicles.

Advancement in technologies of devices and measuring techniques may be seen in growing accuracy, constant procedure shortening and increase of gained results reliability. Automation is infiltrating in analytics. Special advancement is expected in using robots for acquisition and preparation of samples. Telecommunication coordination between laboratories with different procedures and techniques should accelerate specialist's judgment on all controversial data.

A chart showing the influence of ecological directives on trends of elimination of sulfur from fuels (and with almost the same trend of elimination of chlorine from lubricants) is presented in figure 4. Since there is demand for drastic reduction of quantities, needs for new measuring techniques and knowledge grow. Technically speaking, the accuracy of measurement becomes the central question.

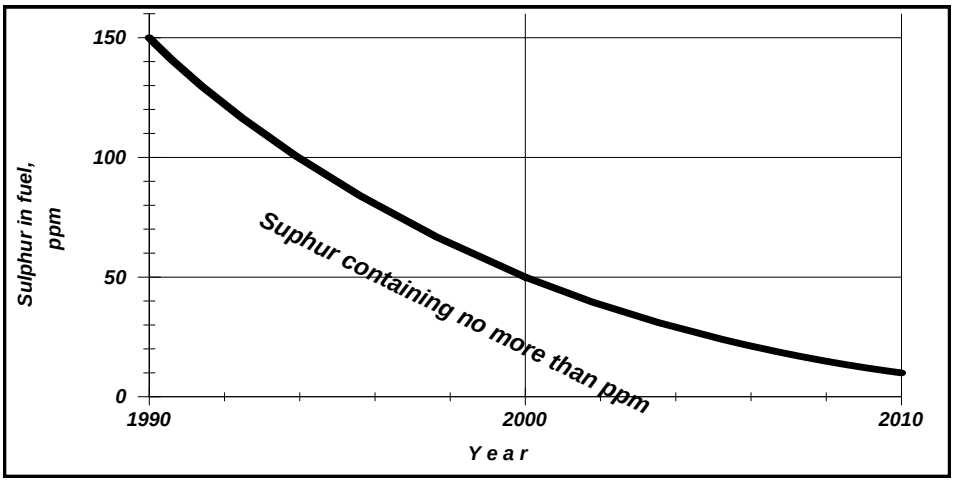


Figure 4: Development basic sampling and instrument settings

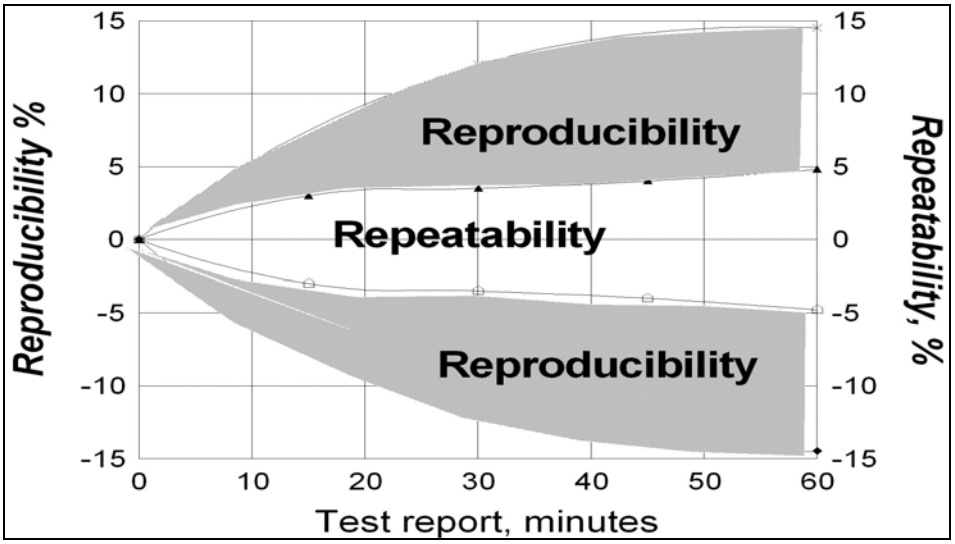


Figure 5: ISO precision data for test repeatability and reproducibility limits

Component producers are no longer sub-contractors, but partners, that are OEMs, with obligation to guarantee quality, installing and recycling of their products. A new spare part may be bought only when the old part is given back to the producer. Therefore (according to ISO), strict controls are obligatory through all phases of production and application, from customers to repeated and continuous circulation of raw materials.

TRIBOLOGICAL BEHAVIOR OF MACHINE AND OPERATING CONDITIONS

Subjects of tribological optimization are found equally at diesel and SI engines. They are specially emphasized at diesel engines because they are more robust in dimensions due to greater forces and moments.

Connection between fuel consumption and mechanical losses at IC engines is direct and clear. The largest portion of losses develops during mechanical sliding motion of parts. Auxiliary power units and equipment necessary for both the engine and the vehicle make the second portion of losses. The third portion is made by: lubricants, hydraulic fluids, coolants, brake fluids, grease and similar.

Regular delusion is the one regarding the value of mechanical efficiency of IC engine. The efficiency of 90% for SI engines and 80% for diesel engines is considered at nominal regime. At partial loads, these values are half their size.

Knowledge on structure of losses is also not at high level. Strategic decisions have been reached recently regarding the equipment of vehicles, engines and common devices. An alarm took place several years ago, while the race towards overall automation was on. At one moment, the sum of consumers was growing that fast, that nominal voltages of 14 V had been increased three times, to 42 V. Similar multiples were foreseen for installed power for equipment and devices. New ecological regulations were followed by revisions and by rigorous conclusions. There is no place for wasteful dimensioning. Energy savings and ecological correctness are exactly the most important determinants of future development of all parts and all systems of the vehicle. Therefore, electric installations of new vehicles operate on certified 12V voltage, with obligatory application of all kinds of modern technologies.

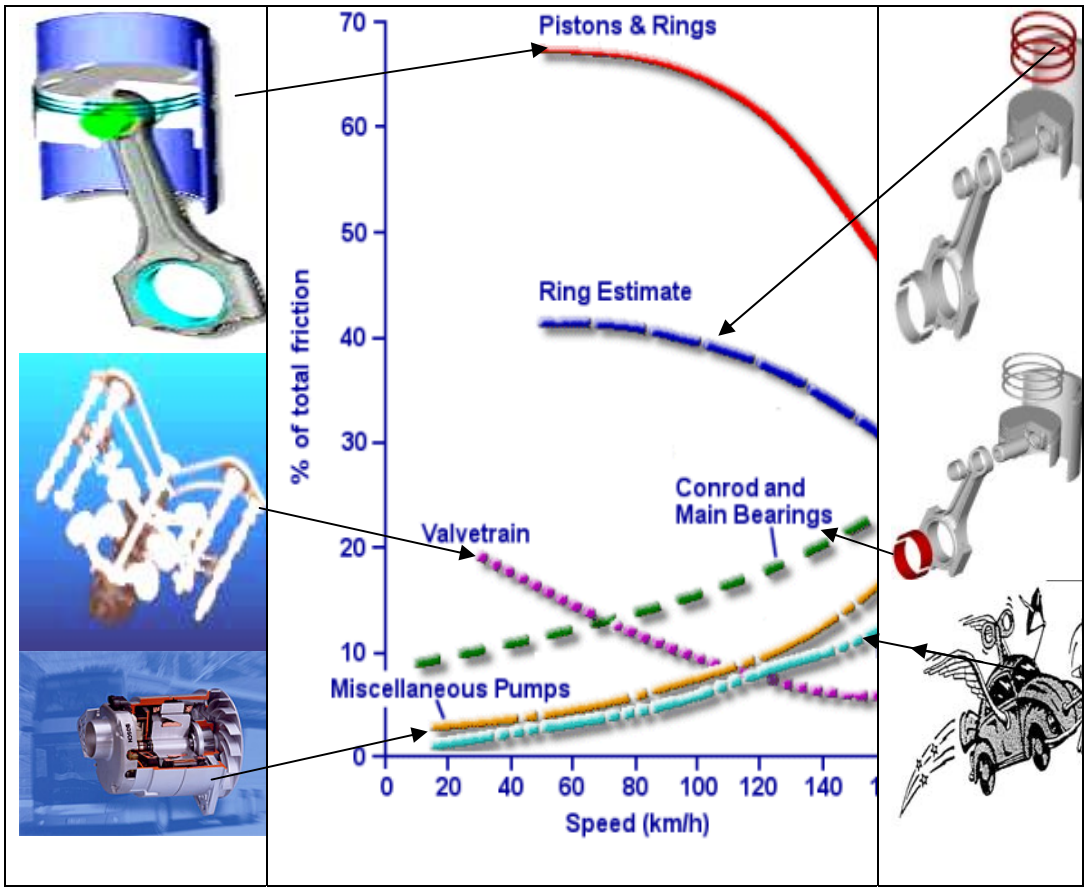


Figure 6: Friction diagram main vehicles system versus speed

The third source of delusions relies on a great contribution of fuels and lubricants to better ecology and smaller fuel consumption. Advertisements for motor oils are especially incorrect. There still is criterion that the only good advertisement is the advertisement that offers a two-figure "savings".

Friction balance in passenger vehicle's engine as a function of speed is presented in Figure 6.

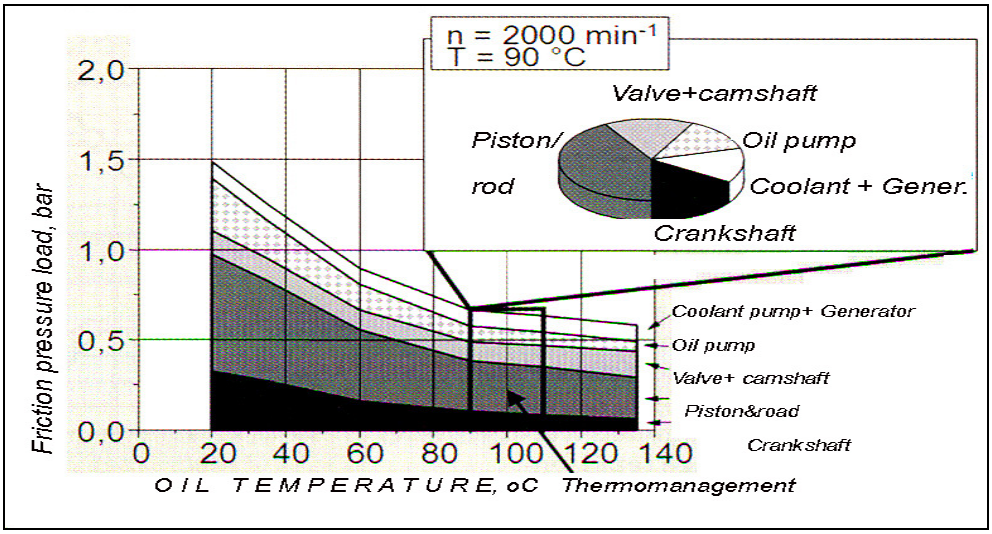


Figure 7: Friction versus oil temperature- 2 lit gasoline engine [5]

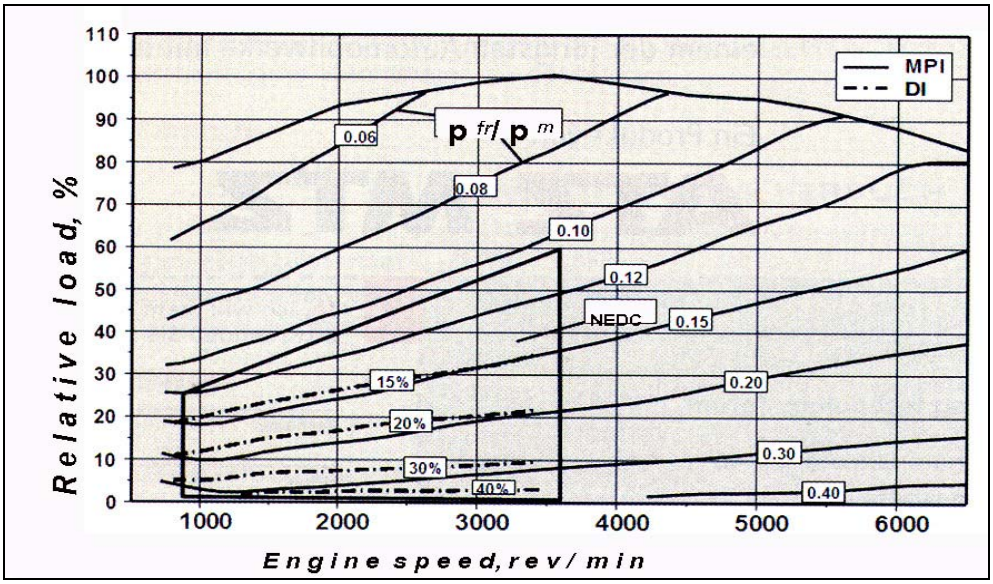


Figure 8: Share of friction in engine map- 2 lit gasoline engine [5]

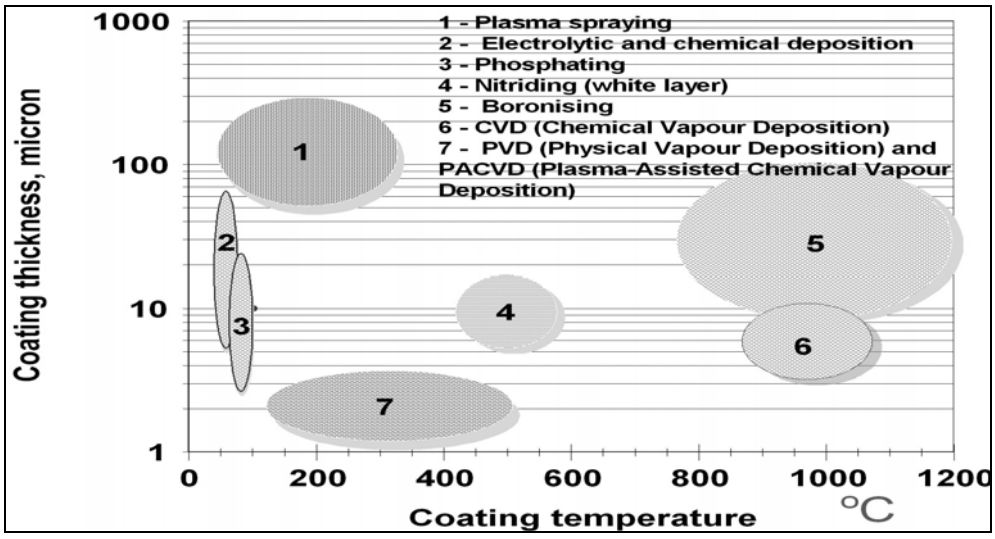


Figure 9: Processes for the surface treatment of tools and precision components

The engine is the main source of mechanical losses with its systems like engine mechanism (pistons, piston rings, piston rod and crankshaft) and cylinder block, and then, there are numerous common systems and devices of vehicles and engines. Major effects are gained by acting on main sources of friction. Improvements of vehicles and engines equipment and devices have only partial influence on smaller fuel consumption.

Valid European test for NEDC emissions dictates the reduction of emission for 30% until year 2012. Special attention is given to SO_2 quantities and to smaller fuel consumption.

Alternative fuels and new formulations of lubricant and, especially for additives, can lead to increase in economy and to SO_2 emission reduction. Proving of such expectations for simplified laboratory and simulation conditions, way apart from real conditions is quite popular. Although a possible contribution of fuels and lubricants is not discussed here, it must be noticed that all kinds of tribological optimizations have purpose only if they are based on a complex discussion of influence of materials, technologies and operation conditions.

Majority of previous cognitions regarding the heat balance are based on high mechanical efficiency from data for stationary conditions.

Figure 7 shows the friction data acquired in stationary regimes.

If only imaginary medium, stationary regime is assigned to NEDC test drive, then engine speed would be 2000 min^{-1} and fluid temperature would be around 90 ^oC. An NEDC test drive is different because it consists from urban and interurban road sections.

NEDC test starts from environmental conditions, 20^oC. Then, two thirds of the test are driven with engine and its devices cooled down. Engine mechanism and valve train make three quarters of mechanical losses at engine. Cooling system and lubrication system are main contributors to increased friction of all movable assemblies.

Modern forced engines have maximal oil and water temperatures over 100^oC, up to 140^oC. This means that, if those systems should be quickly brought to nominal state, then a larger part of NEDC test would be realized with more efficient driving, lower total emission and lower CO_2 emission. Subjects with such content are fostered in vehicle industry research facilities under the general term "thermo-management".

NEDC drive regime is taken into the universal diagram for 2l SI engines (MPI – injection into intake manifold and DI – direct injection into cylinder).

Relative mechanical losses are proven by medium friction (p_{tr}) to medium effective pressure (p_{me}) ratio. Whole cycle is executed in the area of mechanical efficiency 10% to 40% lower then nominal. This means that fuel consumption is proportionally higher. True explanation for such huge increase of friction at partial loads is found in cold engine having all measures and tolerances far away from nominal.

Let us pay no more attention to relation between stationary and dynamical conditions and only mention strategic visions from the area of tribological perfection through a review of design optimization of IC engines.

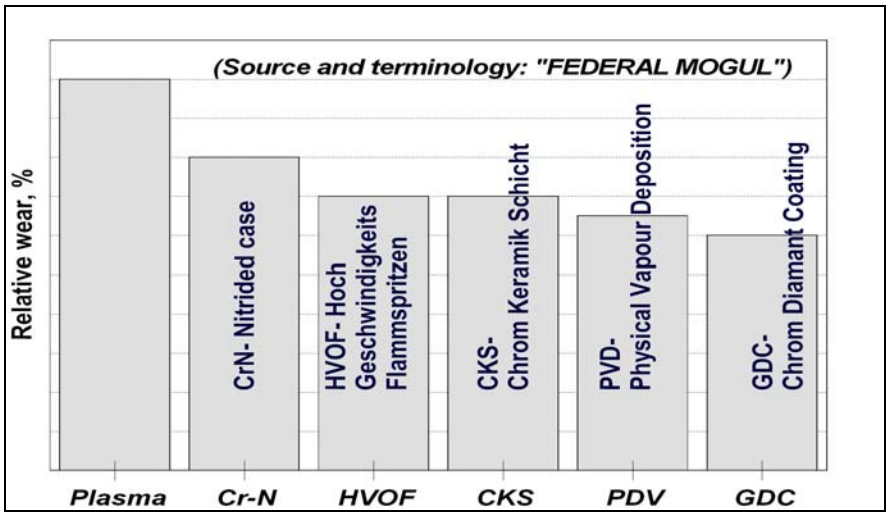


Figure 10: Comparison of relative wear resistances (plasma=100%) top piston rings in European passenger car with gasoline and diesel engines

Two new technologies are the most interesting. The first is related to surfacing and application of protective layers and coatings that give lower friction and smaller wear. The second is related to laser machining of cylinder liners of SI and Diesel engines.

There are several methods for application of protective layers on piston rings, pistons and cylinder liners in serial application at larger companies. Basic information on physical, chemical and combined methods for final surfacing of machine parts are presented in Figure 9. Each technology prescribes a specific structure for material from which a layer is generated.

Figure 10 shows data on relative effect of such procedures on piston rings from "Federal Mogul" company.

Domestic automobile industry gets a great help from components producers. We specially take into account "PDM" company from Mladenovac and "MOTINS" company from Novi Sad. both companies continuously produce parts for high quality engines and actively work on improvement of their products. Therefore, it is our opinion, that the application of described technologies is realistic at both of our producers.

TRIBOLOGICAL OPTIMIZATION OF PISTON ASSEMBLY AND CYLINDER LINER

The main instruction with tribological optimization orders the transfer of all bordering cases in hydrodynamic lubrication. In accordance with this request, we have shown in Figure 11 a new solution of the piston with tribo-pads and cylinder liner made from aluminum, with tribo-inserts [15].

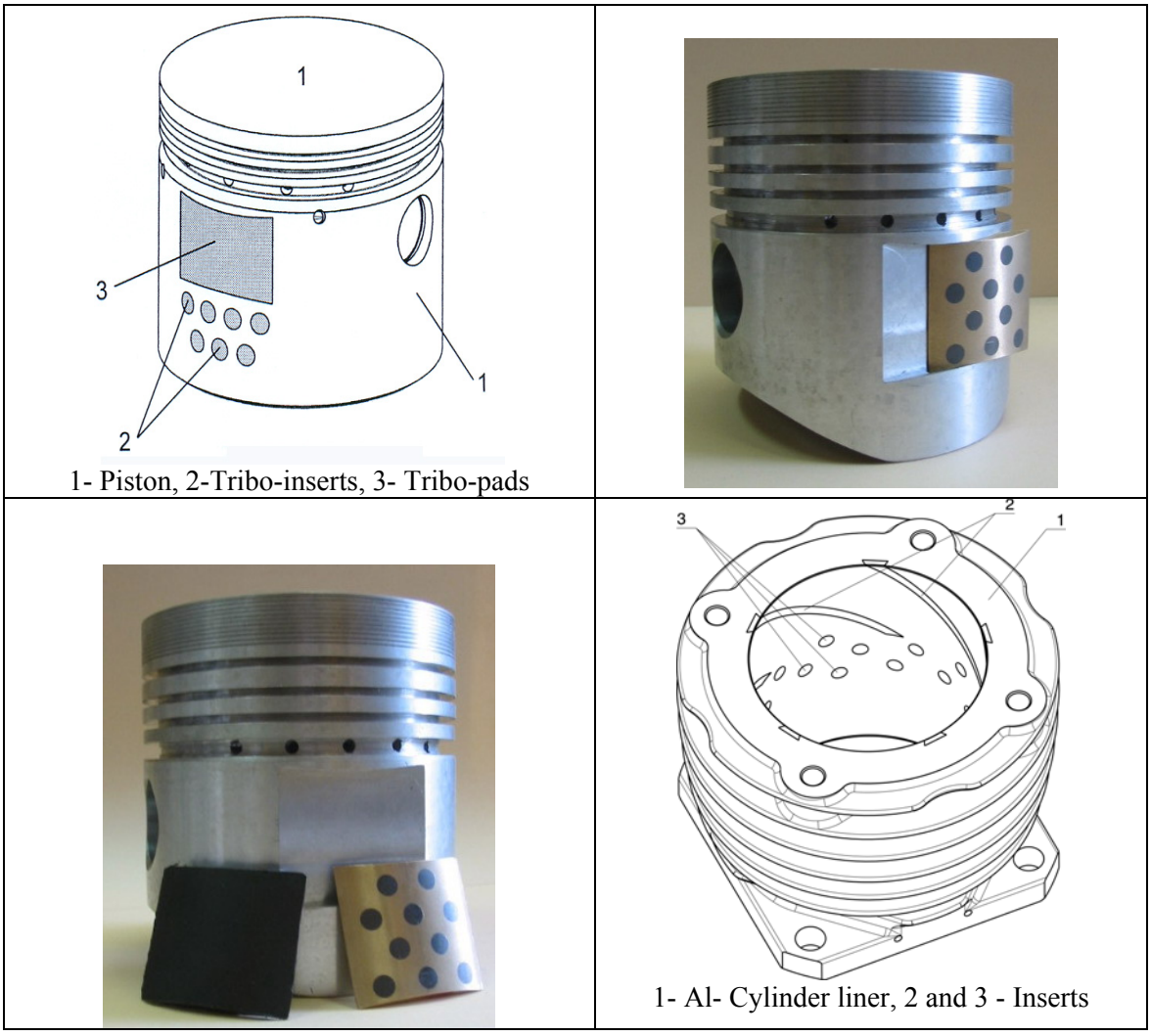


Figure 11: Piston and cylinder with tribo – pads and inserts [16,17,18]

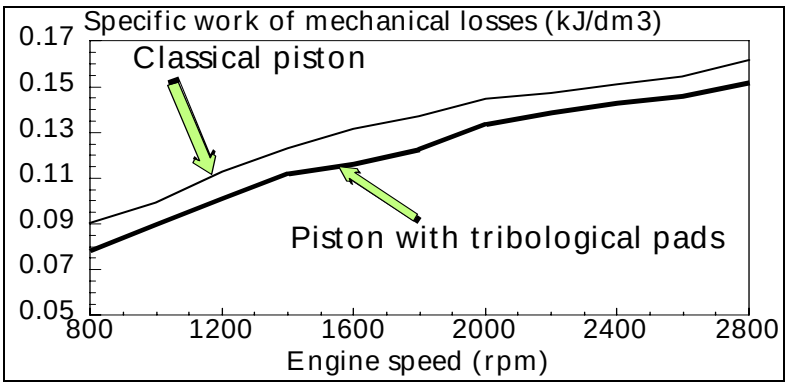


Figure 12: Effect of a tribological pads on mechanical friction in IC engines [15]

When we tested one variable of the tribo-pads at the LDA 450 engine ("Lombardini"-Italy, licensed by DMB,"21 Maj", Belgrade), we obtained the data shown in Figure12. With the increase of normal forces (from compression) and the number of rpm, specific work of mechanical losses gets lower then 5% then with classical piston made from aluminum and cylinder made from grey cast iron.

The main task of the tribo-pads is to decrease friction between piston and cylinder, especially at engine-starting regime. Besides that, they transfer wear of piston on the easily replaceable pads, so that in the future of remount the piston group comes down to the replacement of the used-up rings and pads. Piston becomes only the bearer of parts that are spent and can be easily replaced.

Fuels and lubricants can contribute around 3-5%. The auxiliary power units are now under inspection, so the current prognosis is that they contribute around 10%.

We surely cannot forget her something that is not only a reminder, but is rather an ultimatum: the optimizations have to be performed in all operating conditions.

CONCUSIONS

In order to achieve high-level values of effective efficiency ratio, tribological optimization of IC engines must be done together with thermodynamic optimizations.

Engines heat balance implies that the greatest reserves are in increase of efficiency ratio *at partial loads*. Thereby, we must not forget something that is not only a reminder, but is rather an ultimatum: ***the optimizations have to be performed in all operating conditions.***

The major part of mechanical losses takes place at piston assembly, first of all at piston rings. Improvements in design of piston and its skirt (e.g. implanting the tribo-pads and tribo-inserts), *application* of new coatings and layers on piston rings and cylinder liners (again, implanting the tribo-pads and tribo-inserts), directly leads to decrease in fuel consumption.

Preservation of manufacturing quality of piston engine compressor and pump parts in view of satisfaction of design tolerances: spatial shape, dimensions, normality, parallelism and surface quality, essentially lowers mechanical losses.

Cold start, low loads, cold engine parts and unprepared lubricants emphasize the heaviest operation conditions. Friction is the highest then and friction surfaces wear and deform. If, for example, lubricants were quickly heated, then all sliding couples would be nicely lubricated. The use of multi-grade oils having small variations of viscosity, together with other procedures of "thermo-management", are measures that may lead to noticeable improvement of engine tribological characteristics, decrease in fuel consumption and lower emissions in everyday exploitation of the vehicle.

LISTS OF ACRONYMS

ASTM - American Society for Testing and Materials
DI – Direct Injection into cylinder
DMB - "21 Maj" Beograd
ECE – Economic Commission for Europe
EU - Europe Union
FTP – Federal Test Procedure
FZG - Forschungsstelle für Zahnräder und Getrieböl
MPI – Multi Point Injection into intake manifold
MOTINS – Motorna industrija Novi Sad
NEDC - New European Driving Cycle
OEM- Original Equipment Manufacturer
PDM – "Petar Drapšin" Mladenovac
SI - Spark Ignition
TQC - Total Quality Control

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