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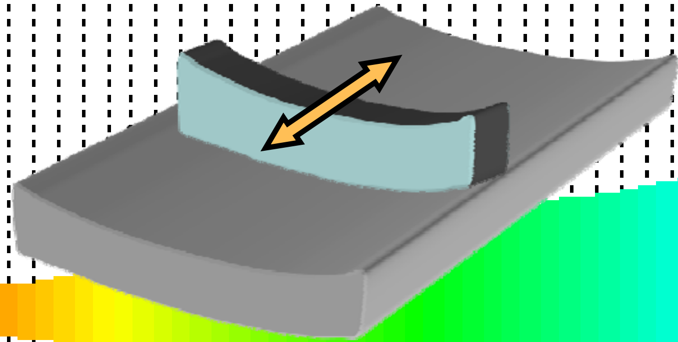
Parasitic Energy Losses



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Argonne National Laboratory

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2009 US DOE Hydrogen Program and Vehicle Technologies Program

Annual Merit Review and Peer Evaluation Meeting

May 18-22, Washington D.C.

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U.S. Department of Energy

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Overview

Timeline

- Project start date FY 06
- Project end date FY 13
- Percent complete 33%

Budget

- Total Project Funding ~1M
  - DOE Share ~1M
  - Contractor Share* ~150K

- FY 08 200K
- FY 09 175K

* includes in-kind contribution by subcontractor

Barriers

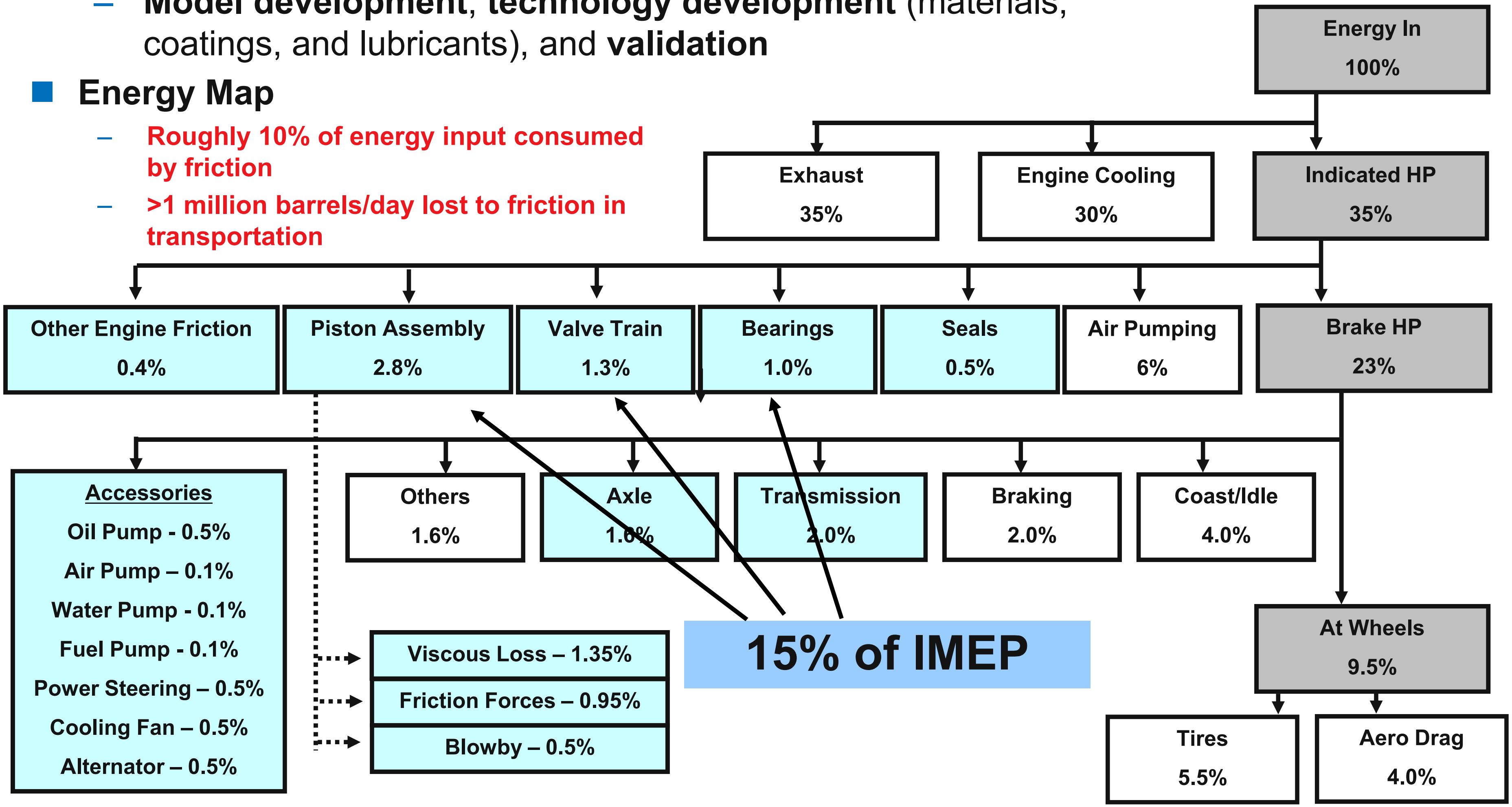
- Barriers addressed - FCVT/VT Heavy Vehicle Systems Barriers (3.1.2.8)
  - Safety, Durability, Reliability
  - Computational models, design and simulation methodologies
  - Higher vehicular operational demands

Partners

- Ricardo & University of Michigan
- Mahle
- Additive and Lubricant OEMs
- TARDEC (leveraged funds)

Relevance/Purpose/Objective of Work - more energy lost to friction that delivered to the wheels

- **Reduce PARASITIC FRICTION to Increase FUEL EFFICIENCY and Reduce Use of Petroleum**
  - **Model development**, **technology development** (materials, coatings, and lubricants), and **validation**
- **Energy Map**
  - **Roughly 10% of energy input consumed by friction**
  - **>1 million barrels/day lost to friction in transportation**



Significant Reduction in Petroleum Consumption by Reducing Parasitic Friction Losses

	Petroleum Used (MBPD)	Engine Efficiency Potential (%)	Engine Petroleum Savings (kBPD)	Driveline Efficiency Potential (%)	Driveline Petroleum Savings (kBPD)	Total Savings (kBPD)
HVs	2.5	3/(10)	75/(250)	2/(4.2)	50/(105)	125/(355)
LTs	4.3	3/(10)	129/(430)	1.5/(2.7)	65/(116)	194/(546)
Cars	4.7	3/(10)	141/(470)	1.4/(2.5)	66/(118)	207/(588)
Total	**12**		**345/(1150)**		**181/(339)**	**526/(1504)**

- Consumption of petroleum can be reduced by **0.5 to 1.5 MBPD**
    - 0.1 to 0.4 MBPD in HVs
    - 0.2 to 0.5 MBPD in LTs
    - 0.2 to 0.6 MBPD in Cars

- **Parasitic Friction Technologies Applicable to ALL Vehicle Platforms**

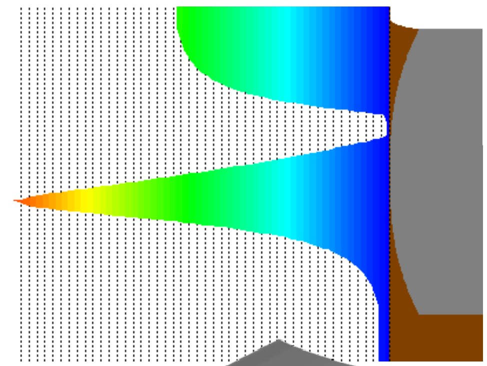
Project Milestones

- FY 08 (completed)
  - Application of lab-tribometers to screen and identify potential low-friction solutions - superhard nanocomposite coatings and boric-acid based additives
  - Ring-on-liner studies of boric-acid based additive on friction - commercial additive package reduced ring/liner friction

- FY09
  - Developed experimental technique to characterize piston-skirt/liner friction (on-schedule)
  - Established collaborative interaction with parts supplier to model lab results using mechanistic friction codes - assembling experimental data package for input to computer code
  - Complete single-cylinder validation tests (in-progress) [Go/no-Go Decision for Phase III additive and coating tests]

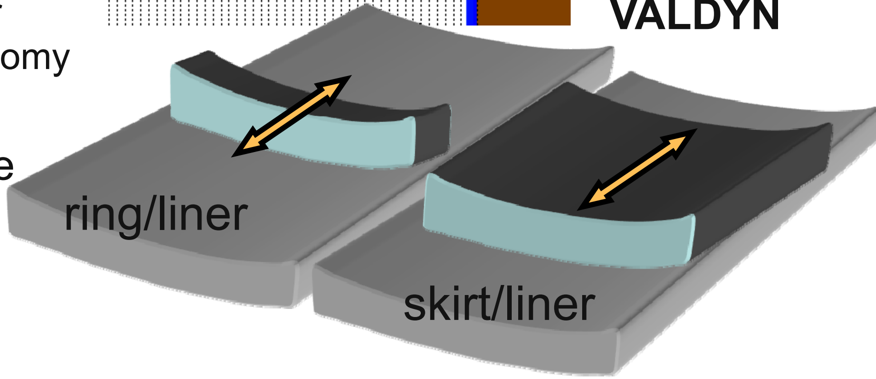
Approach

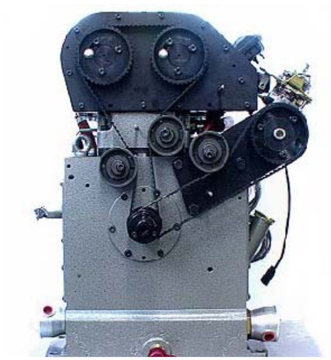
- **Develop and Apply Mechanistic Models** of Friction (Boundary and Viscous) Losses to Predict Parasitic Losses as a Function of **Engine Conditions** (Load & Speed), and **Tribological Conditions** (Boundary Friction and Oil Viscosity)
  - Scale fuel consumption as a function of FMEP and IMEP for a prototypical HD diesel engine
  - Predict the impact of low-friction (boundary-layer friction) and low-viscosity lubricants on fuel economy
- **Evaluate/Screen the Potential of Candidate Surface Treatments and Additives** to Reduce Boundary Friction Under Lab Conditions Prototypical of Engine Environments
  - Benchtop friction tests using prototypical engine components
  - Impact of materials, coatings, surface texture, and lubricant additives and viscosity
- **Validate Codes/Models and High-Potential Solutions** in Fired Engines Using In-Situ Friction Measurement Techniques
- **Demonstrate efficiency improvements** in multi-cylinder engines



RICARDO

RINGPAK
PISDYN
ORBIT
VALDYN

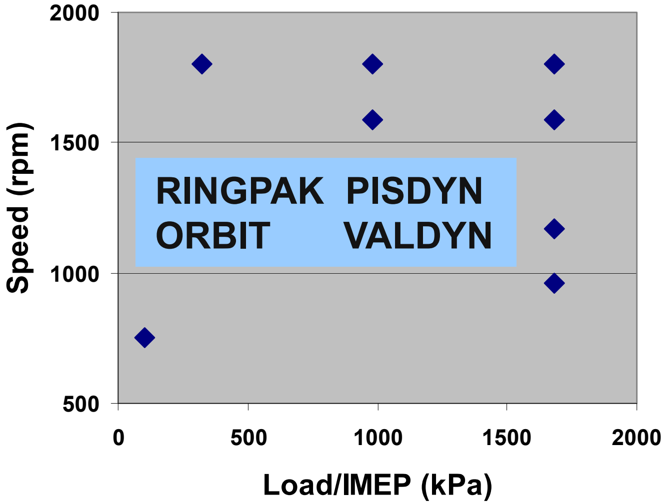




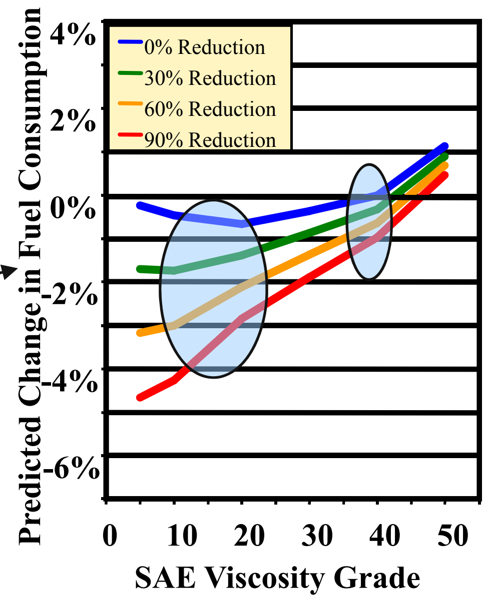
W.E. Lay Automotive Laboratory

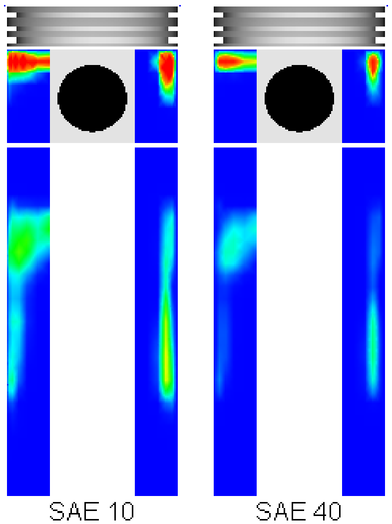
Integrated mechanistic models of asperity and viscous friction to predict impact of friction on fuel economy

FMEP calculated at 8 different modes and weighted to predict effect on fuel consumption for a HD driving cycle

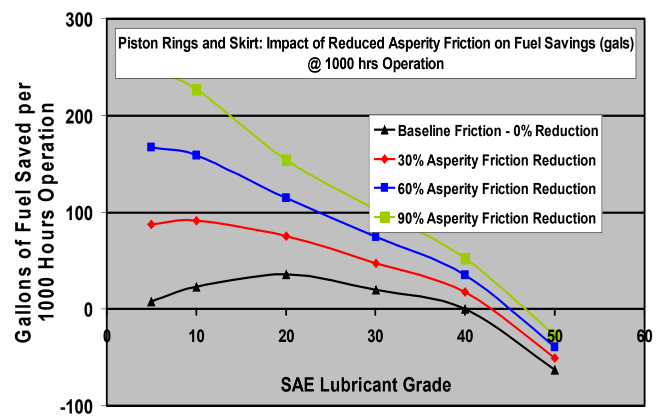


Effect of boundary friction and viscosity on fuel economy and wear severity





- Integrated PISDYN, RINGPAK, VALDYN, and ORBIT codes to calculate FMEP at different engine conditions. Scaled fuel economy to IMEP to predict impact of boundary friction and lubricant viscosity
  - Reducing boundary friction alone (by low friction coatings and/or additives) will reduce fuel consumption up to 1 %
  - Reducing viscosity alone will save approximately ½%
  - Low boundary friction enables use of low viscosity lubricants to save up to 4%
  - Fuel savings dependent on weighting factors assumed for each mode

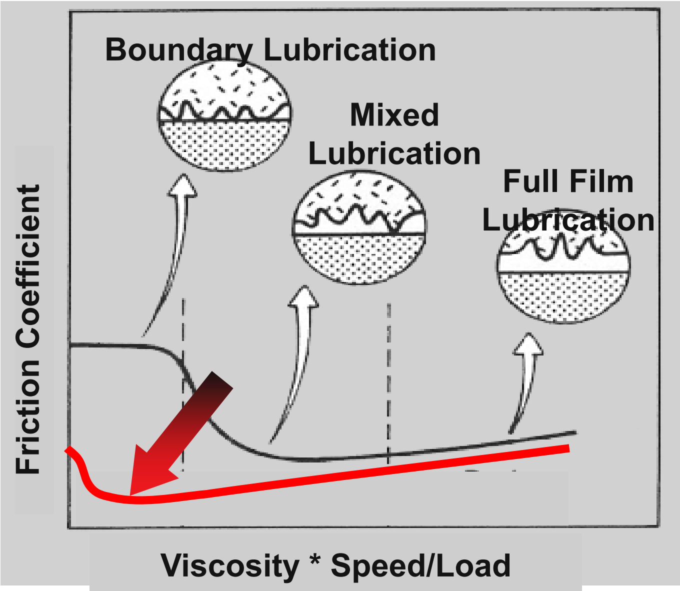


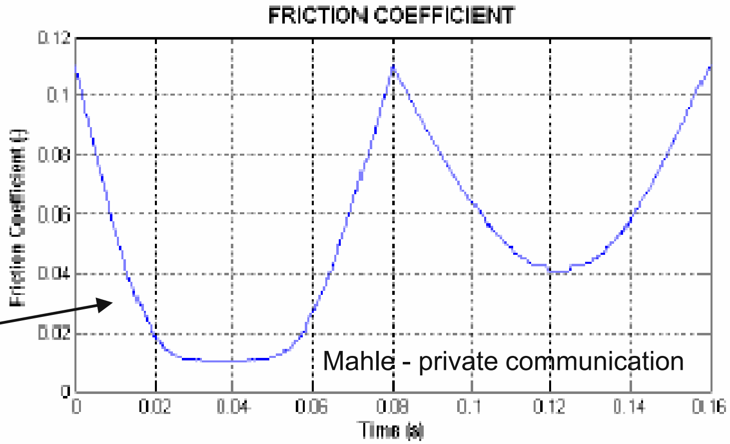
Established collaboration with supplier to develop, test, and model the impact of advanced coatings and additives on ring & liner friction

- Modeling friction data obtained from lab rigs is crucial, especially when lab tests use engine lubricants where asperity and viscous friction mechanisms are present.
- Different regimes of lubrication depending on the degree of contact between sliding surfaces

$$\mu = \alpha \mu_a + (1-\alpha) \mu_v$$

- Boundary lubrication characterized by solid-solid contact – asperities of mating surfaces in contact with one another
- Full-film (hydrodynamic) lubrication in which mating surfaces are separated by an oil film.
- Example at right illustrates impact of non-symmetric ring profile on predicted ring/liner friction
- Modeling needed to interpret experimental data

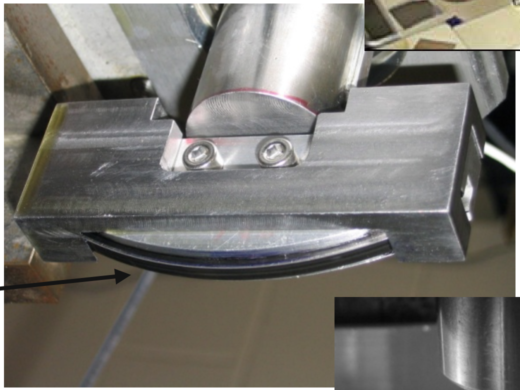




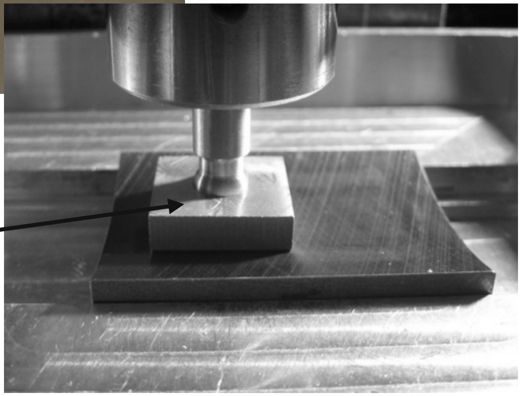
Identified Low-Friction Technologies that Enable Low-Viscosity Lubricants and Maintain Durability/Reliability

- **The mechanistic engine friction models predict impact of lowering friction (asperity or viscous) on fuel economy…**
- **But… the models don't tell us how to lower friction, or, how to increase durability and reliability, or what options are available**
- **Therefore…the second objective of this project evaluates potential technologies to achieve the 30, 60, … 90% reductions in friction.**
  - Pin-on-disc configuration – simple to use and provides quick evaluation of friction (and wear) under well-defined geometry
  - Ring-on-liner configuration – more complicated, prototypic configuration, uses coupons obtained from standard components (rings)
  - Skirt-on-Liner configuration - uses skirt and liner coupons obtained from commercial pistons and liners



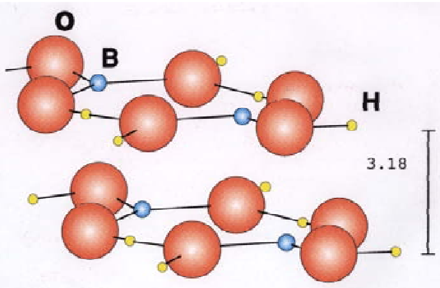


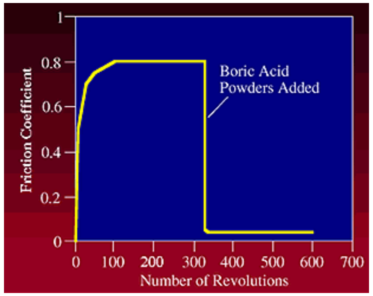
10 to 50 N/mm
(3 - 16 N/mm^2)



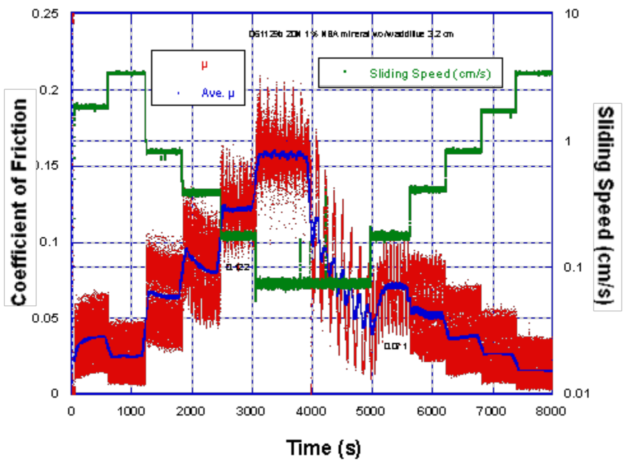
0.2 to 2 N/mm^2

Previous studies identified boron-based additive technologies to reduce friction



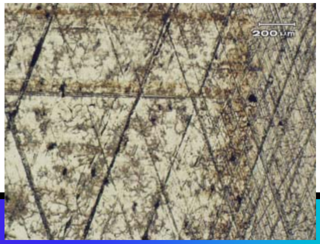


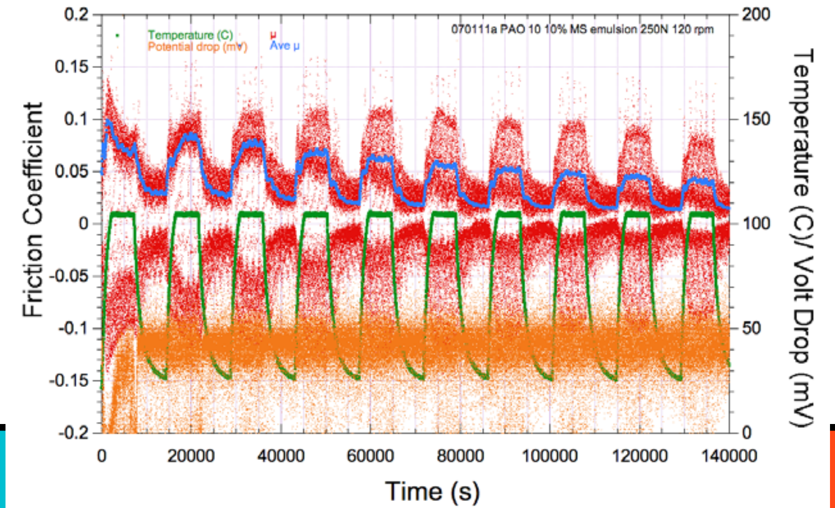
- Based on extensive R&D at Argonne on layered structure of boric acid (BA)…
  - Initial studies on solid BSA films demonstrated dramatic friction reductions (dry sliding conditions)



- ….subsequent activities using ball-on-disc configuration examined performance as a lubricant additive (with liquid lubricant)

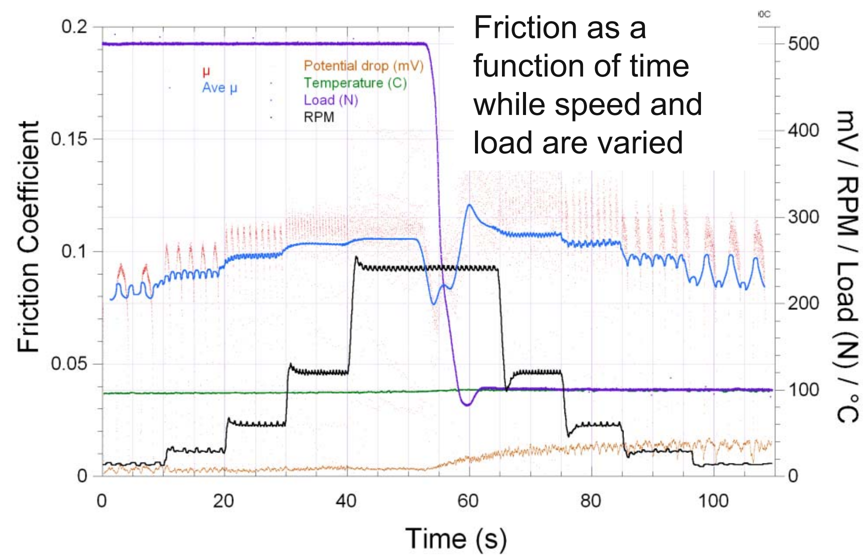
- Recent activities demonstrated low friction performance using components on ring/liner simulator
  - 50 % friction reduction

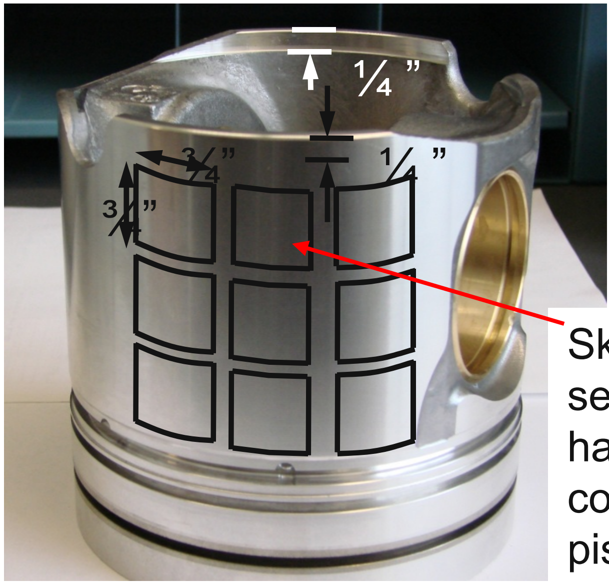




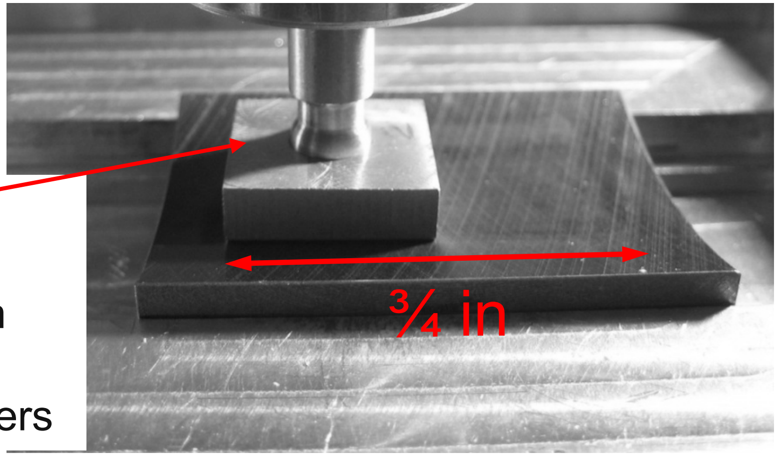
Current activities adapted ring-on-liner test rig to simulate piston-skirt-on-liner friction. Use segments of piston skirts sliding against cylinder liner segments

- Reciprocating test rig was modified and test protocols developed to test segments of piston skirts that reciprocate against liner segments. Loads and speeds selected to mimic in-situ tribological conditions



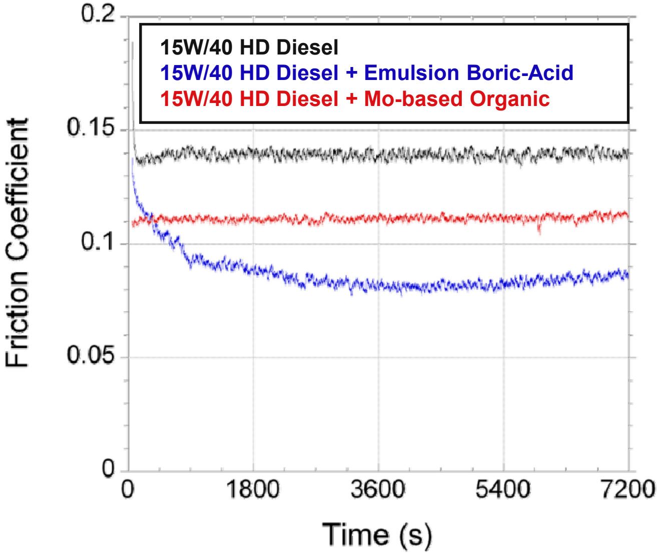


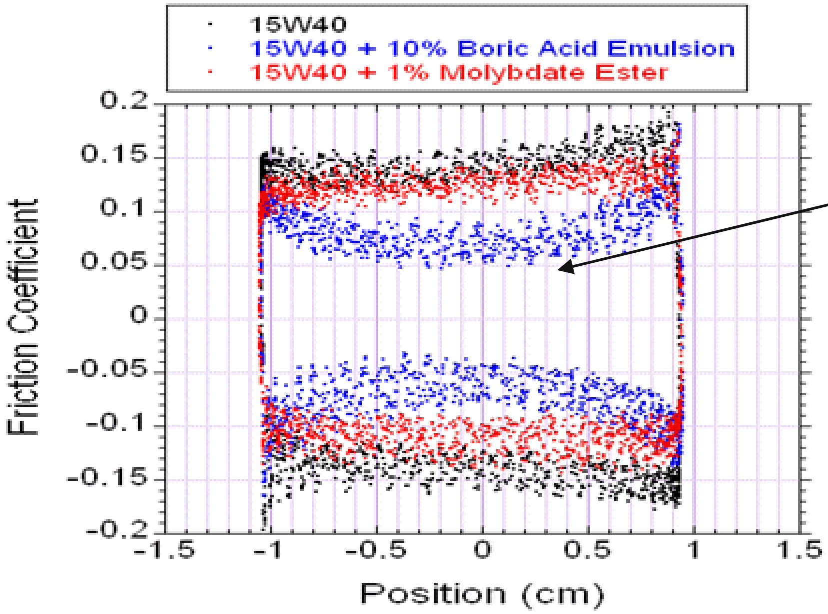
Skirt and liner segments harvested from commercial pistons and liners



Accomplishment - Demonstration of friction reduction in commercial diesel lubricant using an emulsion based boric-acid additive - 40 % reduction

- Skirt-on-liner tests
  - 105 C, 120 rpm, 250 N
- Boundary friction reduction
  - 20 % reduction for Mo based liquid additive
  - 40% reduction for an emulsion boric-acid based additive

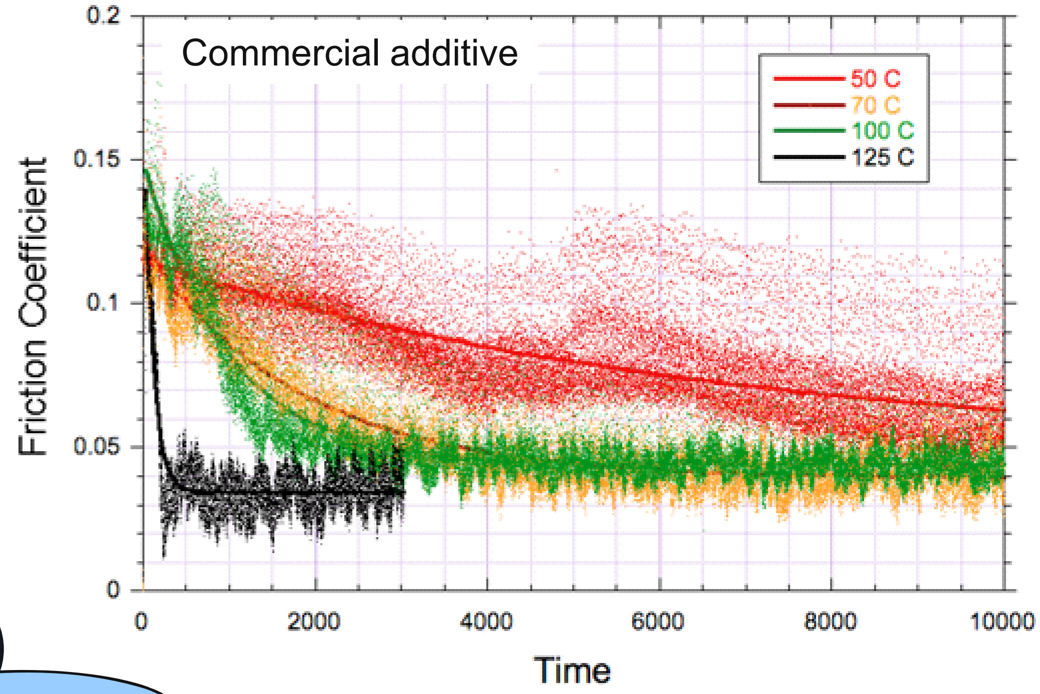


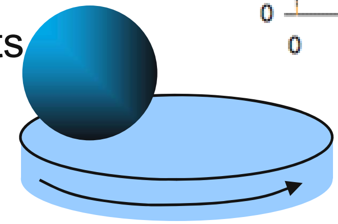


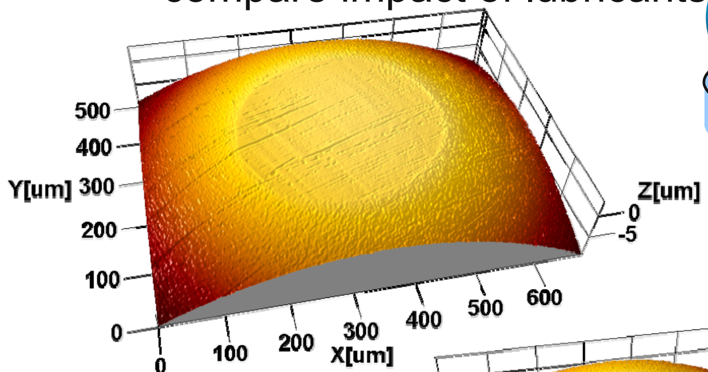
- Area under the curves representative of friction work per cycle
  - Baseline (15W/40) is in boundary friction over entire transverse of skirt
  - Molybdate ester additive produces lower boundary friction
  - Emulsion BA additive providing lower boundary friction and transition to mixed lubrication as indicated by lower friction at midstroke

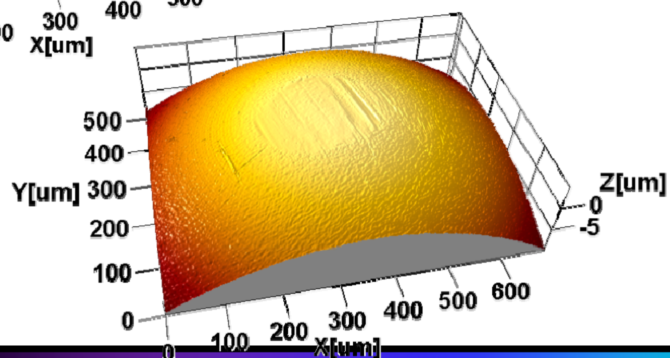
Previous studies using pin-on-disc configuration identified potential additive solutions

- Systematic studies at relatively low speeds provide detailed data on the impact of additives (commercial and experimental) on **boundary film lubrication**
  - Develop test protocols to compare impact of lubricants





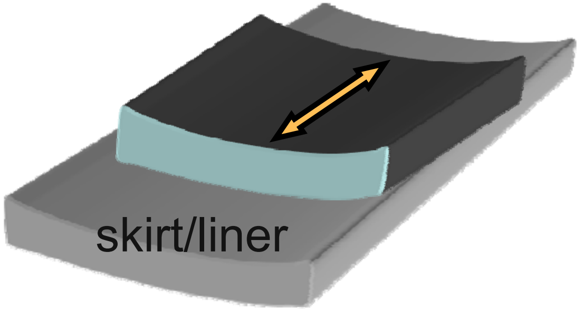




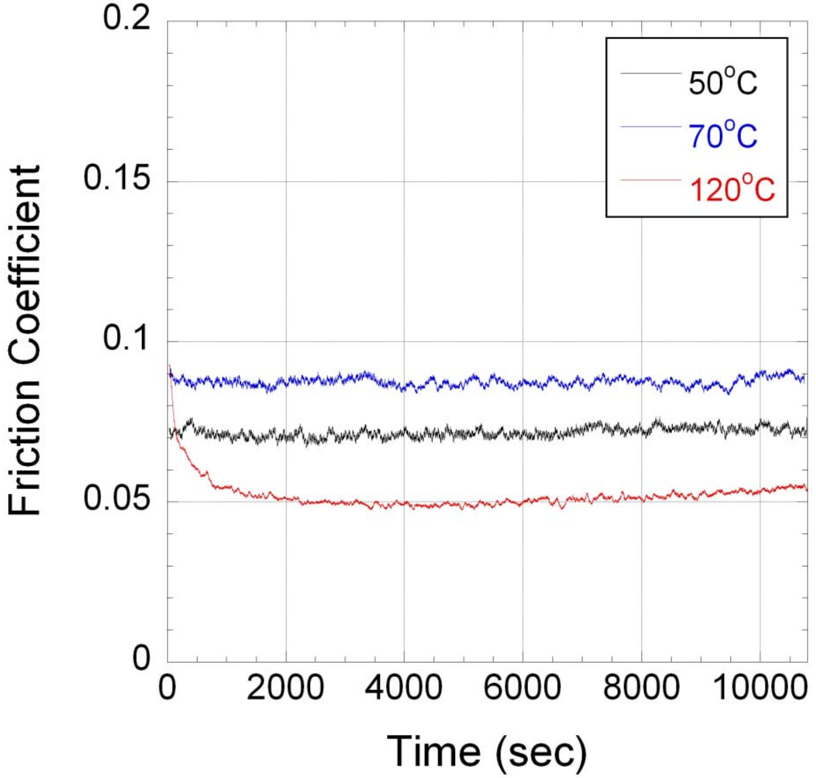
- Quantitative 3-D imaging of test coupons provide detailed information on the impact of lubricants on wear/durability

- **Tests initiated in FY09 to examine friction behavior using skirt-on-liner configuration.**

Skirt on liner tests confirm low-friction behavior of additive under low-stress conditions…but modeling of experimental data required.



- Low-stress skirt-on-liner tests on commercial additives confirm low-friction behavior obtained with high-stress (pin-on-disc) tests….
- ….however, the ranking of the friction curves (at right - friction at 50C is lower the friction at 70C) does not necessarily agree with the pin-on-disc data
- Future activities will include modeling of the skirt-on-liner configuration to include viscosity-temperature effects coupled with low-friction boundary friction



Next stage of model and technology validation incorporates a single-cylinder engine at UM for piston-assembly friction measurement - in-situ friction measurement

- Designed and fabricated the instrumented liner for direct measurements of the piston-assembly friction force

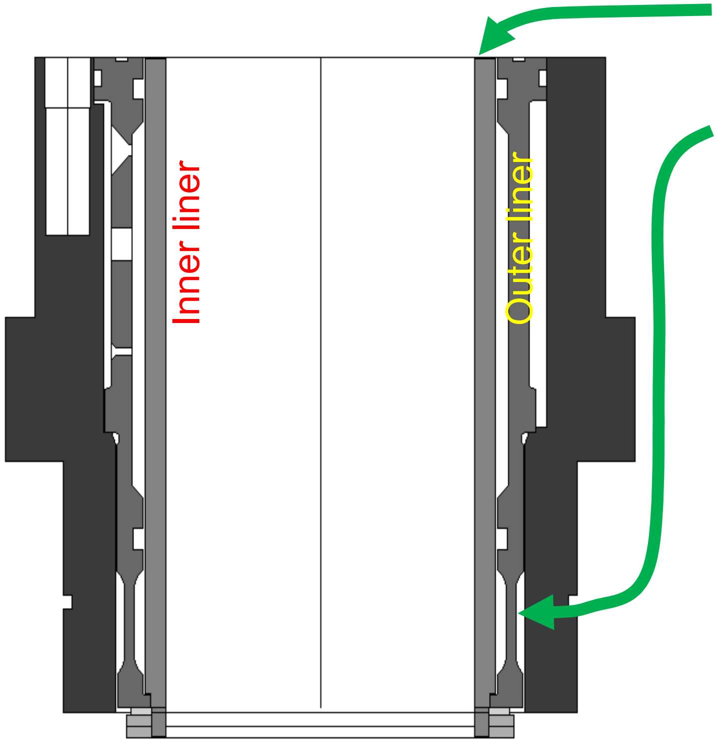
- Established a collaboration with MAHLE and obtained prototype steel pistons in order to create a configuration relevant for the medium and heavy-duty diesels

- Fabricated the new “jug” capable of accommodating the instrumented liner

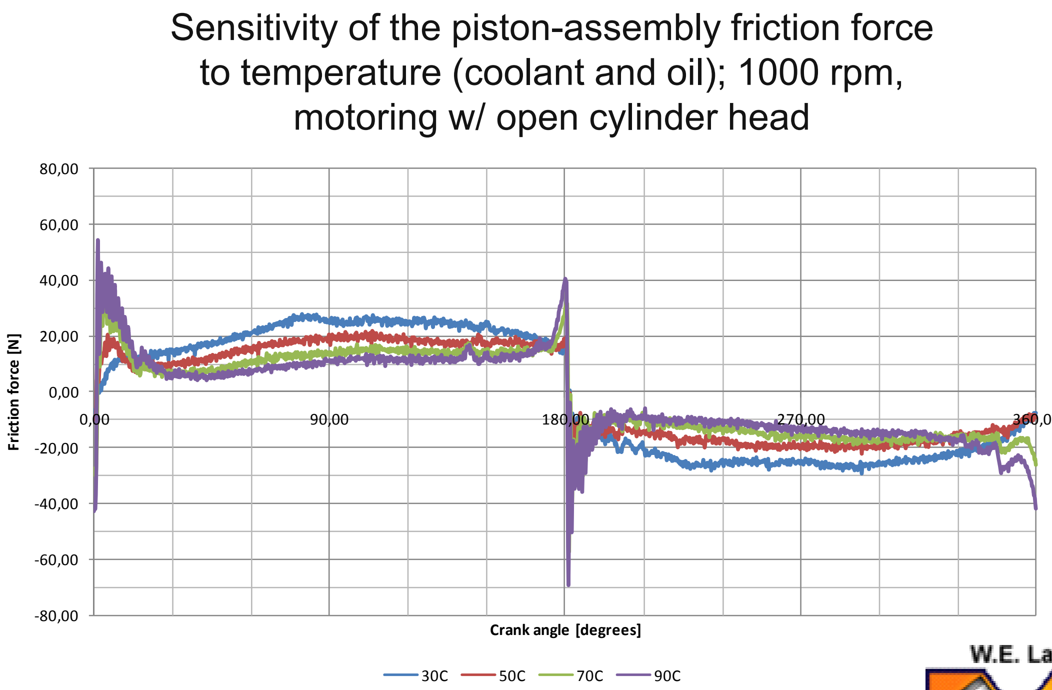
- Worked with Ricardo to finalize the cylinder head assembly for future tests in a firing engine

Single cylinder Hydra engine with in-situ friction capability was assembled and is currently providing information on the impact of temperature (viscosity) on friction in advance of additive tests

- Pressure acting on the upper edge of the inner liner – measure with a piezo-electric transducer
- Force on the outer liner due to friction force on the inner liner and pressure – measure with strain-gages
- Subtract the pressure force from the total to get friction



$$F_{friction} = F_{strain\text{-}gage} - F_{pressure}$$



Future activities will focus on modeling and technology validation

- Modeling - modeling experimental data to delineate boundary and viscosity contributions
- Modeling impact of friction reduction on smaller engines comparable of those used in passenger vehicles (proposed)

- Technology validation using skirt-on-liner and in-situ ring/skirt/liner measurements (UMich/Ricardo)
  - Additives and low-friction coatings

- Characterization of boundary layer films of low-friction technologies

- Identify partners for multi-cylinder engine validation studies

Collaborations

- Parts supplier - providing components for ANL tests, and Argonne providing coated components for evaluation
- Lubricant suppliers - providing oils and additives to Argonne for use in tests
  - Separate DOE project developing advanced nanoadditives
- TARDEC - leveraging activities on DOD contract to evaluate lubricants and additives under severe tribological environments

- Ricardo/UMich - subcontract to develop in-situ single-cylinder engine
  - Considerable in-kind contribution to engineer engine and provide on-of-a-kind conmponents

Summary

- Mechanistic models of parasitic friction losses were developed and integrated to predict the impact of low-friction technologies on fuel efficiency
  - **3-5 % fuel economy savings (0.5 to 1.5 MMBD)**
  - Established collaboration to model experimental friction data
- Lab-scale test protocols were developed and applied to evaluate candidate technologies capable of providing low-friction under boundary layer conditions
  - Pin-on-disc tests identified 2 additive technologies capable reducing boundary friction by 50 to 80%
  - Pin-on disc tests also identified 3-4 coating technologies that exhibit low-friction (30 to 90 % reduction in boundary friction)
  - Ring-on-liner and Skirt-on-Liner tests using prototypic ring, skirt, and liner segments confirmed low-friction properties of a boric-acid additive
  - Further ROL/SOL tests scheduled to evaluate NBA and a commercial additive
- Ricardo/UMich designed and engineered a fired, single-cylinder diesel test rig capable of in-situ ring/piston/liner friction measurements
  - System undergoing motored, and fired shakedown tests
  - FY09 tests scheduled to provide baseline friction data as a function of lubricant viscosity
- Good progress on proceeding from modeling friction impact to validating friction effects in lab/rig/engine tests

Low-Friction Technologies

- **Development of engineered surfaces with low-friction and improved durability & reliability**
  - Low-friction carbon coatings (NFC- ultralow friction carbon, CDC- carbide derived carbon, nanocrystalline diamond, and carbon-carbon composites
  - Superhard nanocomposite coatings
  - Borided steels
  - Laser textured surfaces
  - Additives
- **Evaluation of Commercial Coatings & Materials**