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Heavy Vehicle Systems Optimization
Peer Review

Parasitic Energy Loss Mechanisms Impact on Vehicle System Efficiency
Project 15171

Project Team: ***George Fenske****, Robert Erck, Layo Ajayi, Ali Erdemir, and Osman Eryilmaz*

Argonne National Laboratory

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Parasitic Energy Loss Mechanisms: Impact on Vehicle System Efficiency

21CTP Technical Goal: **Engine Systems: Develop technologies to achieve 55% efficiency by 2012**

Project Objectives

-Increase fuel efficiency by reducing engine friction.

-Develop mechanistic models of parasitic engine losses (and integrate with vehicle system analysis codes – e.g. PSAT)

-Validate models and codes with experiments

-Identify/assess advanced tribological concepts/systems to reduce engine friction (e.g. lubricants, additives, engineered surfaces)

FY 2005/6 Focus

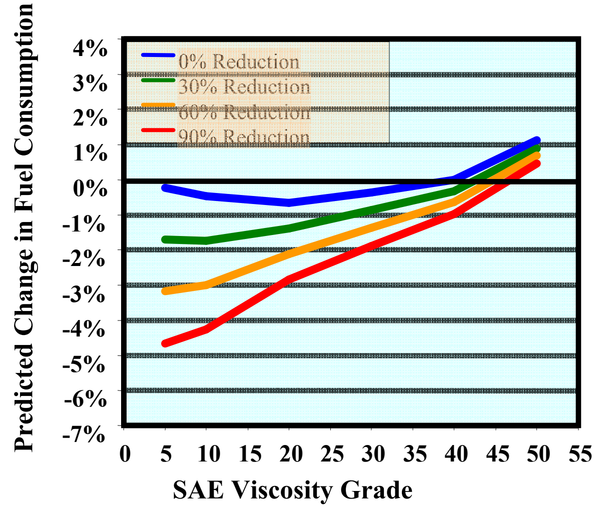
-Model development, application of codes to predict fuel economy savings, and laboratory tests of advanced tribological concepts

-Laboratory tests of low friction additives and coatings

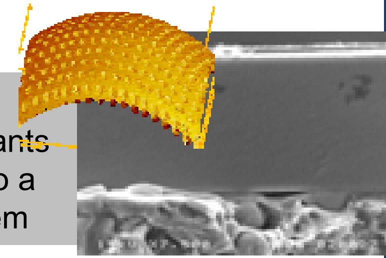
-Design of instrumented single-cylinder diesel engine

Planned Duration
October 2002 to September 2008

DOE Funding/Industry Cost Share
FY05:$125K FY06: $175K/$35K



Integration of materials, lubricants and surfaces into a low-friction system



Principal Investigator(s)
-G. R. Fenske, R. A Erck, O.O Ajayi, and A Erdemir, Argonne National Laboratory, 630-252-5190, gfenske@anl.gov
-L. Oberto, Ricardo Engineering
- Z. Filipi, University of Michigan

Technology Development Manager
Lee Slezak, DOE/OFCVT
(202) 586-2335; Lee.Slezak@hq.doe.gov

Accomplishments

Accomplishment 1: Mechanistic model predictions of .5 to 1.4% fuel savings with low friction surfaces

Accomplishment 2: Mechanistic model predictions of 3-4% fuel savings with low friction surfaces and low-viscosity lubricants

Accomplishment 3: Lab demonstrations of reduced friction surface treatments (up to 80 % reduction)

Significant Future Milestones
Milestone 1: Instrumented single cylinder test rig – Dec 06
Milestone 2: Lab ring-on-liner tests of low-friction additives – Apr 07

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
15171	Systems Optimization	Parasitic Energy Losses	Applied Research	4-06

Relevance to 21CT Goals

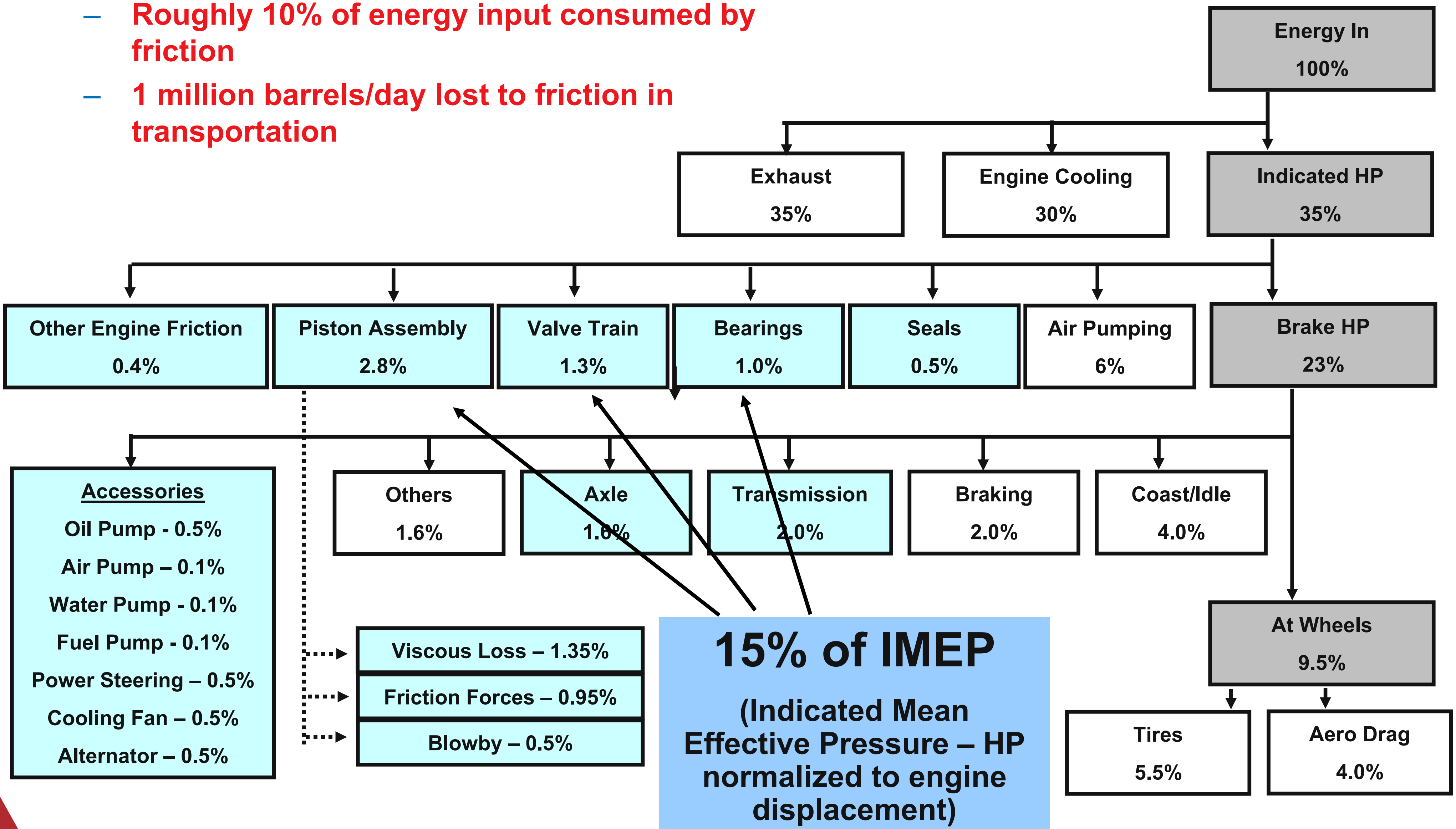
- Reducing friction in engines and drivetrains will increase the fuel efficiency of 21 CT trucks
- Mechanistic models and low-friction engine/drivetrain systems will provide a pathway to achieve engine and vehicle fuel efficiency improvements (50% thermal by 2010; 55% by 2012)
- Collaborations with researchers at:
  - Ricardo Engineering
  - Caterpillar
  - Eaton (CRADA)
  - University of Michigan
  - Suppliers

Technology Transfer

- Subcontractors:
  - Ricardo Engineering
  - University of Michigan
- Potential commercialization pathway
  - Licensing of mechanistic models/codes (Ringpak, Valdyn, Pisdyn, Orbit)
  - Integration of mechanistic models with vehicle system models/codes (e.g. PSAT)
  - Materials & coatings, surface engineering, and additive development.

More Energy is Lost to Friction Than Delivered to the Wheel

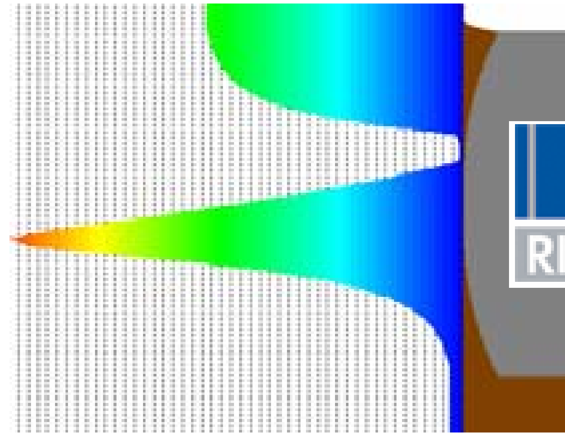
- **Energy Map- Passenger Vehicle EPA Cycle**
  - Roughly 10% of energy input consumed by friction
  - 1 million barrels/day lost to friction in transportation



Objective: Reduce Parasitic Engine Losses to 5-10% IMEP

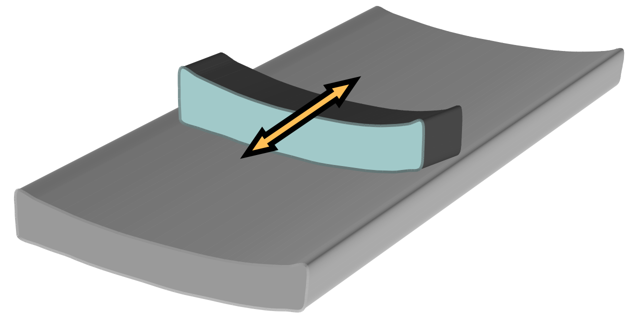
Model low-friction surfaces and lubricant viscosity

- Integrate mechanistic models of friction losses for specific engine components
- Apply codes to predict FMEP at different engine loads and speeds
- Calculate the impact of friction and viscosity on fuel economy



Lab-scale tribological testing

- Benchtop tests to identify potential low-friction material/coating and lubricant systems



Instrumented, fired engine tests

Multi-cylinder engine tests

- Fired, single cylinder diesel engine studies to validate approach
- Multicylinder Engine tests
- PSAT, fleet tests, …..

Technical Accomplishment Summary

- Integrated mechanistic models to predict impact of low-friction surfaces and low-viscosity lubricants on parasitic energy losses (FMEP) and fuel economy

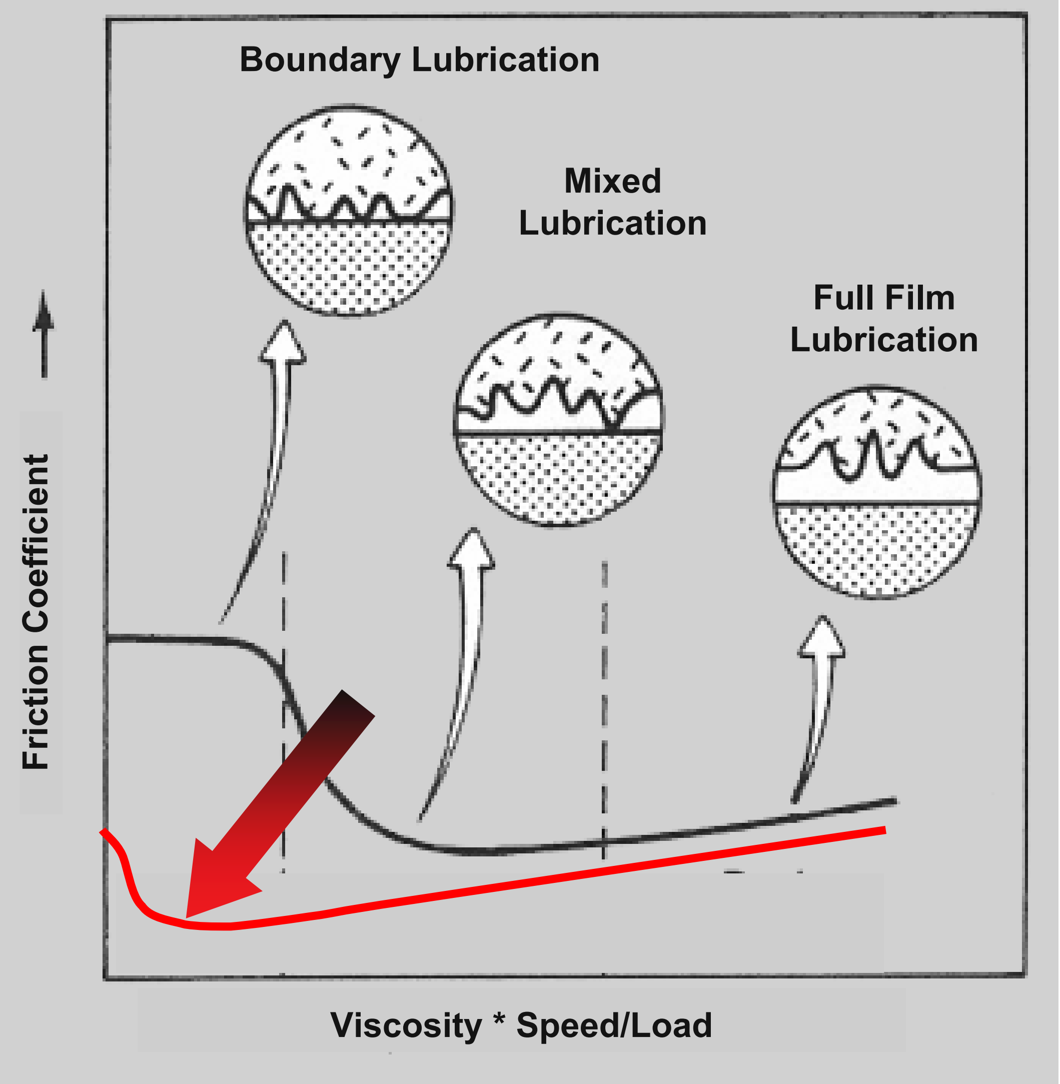
- Developed/selected lab tests to evaluate and optimize advanced low-friction technologies for engine components
  - Comparison with baseline technologies

- Selected approach to validate models and low-friction technologies using a single-cylinder diesel engine
  - Ricardo/U Mich.

- Establishing protocols to translate 8-mode FMEP results into formats compatible with PSAT vehicle simulation toolkits.

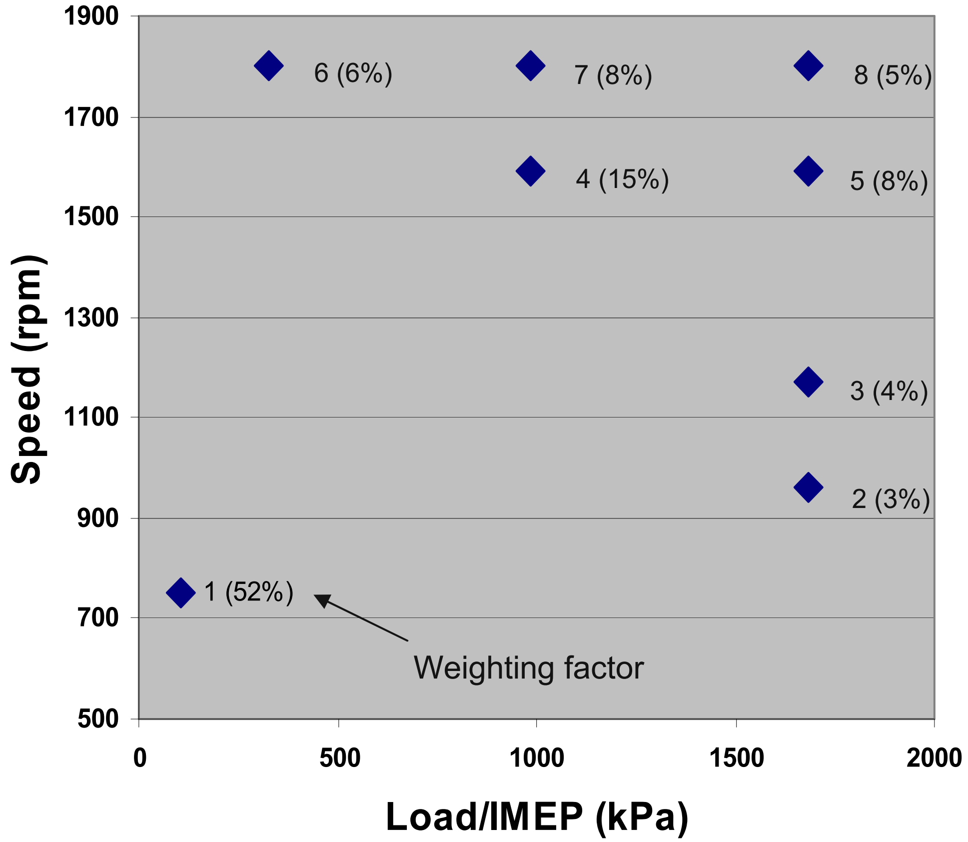
Role of Boundary and Hydrodynamic Lubrication Regimes - Tribological System

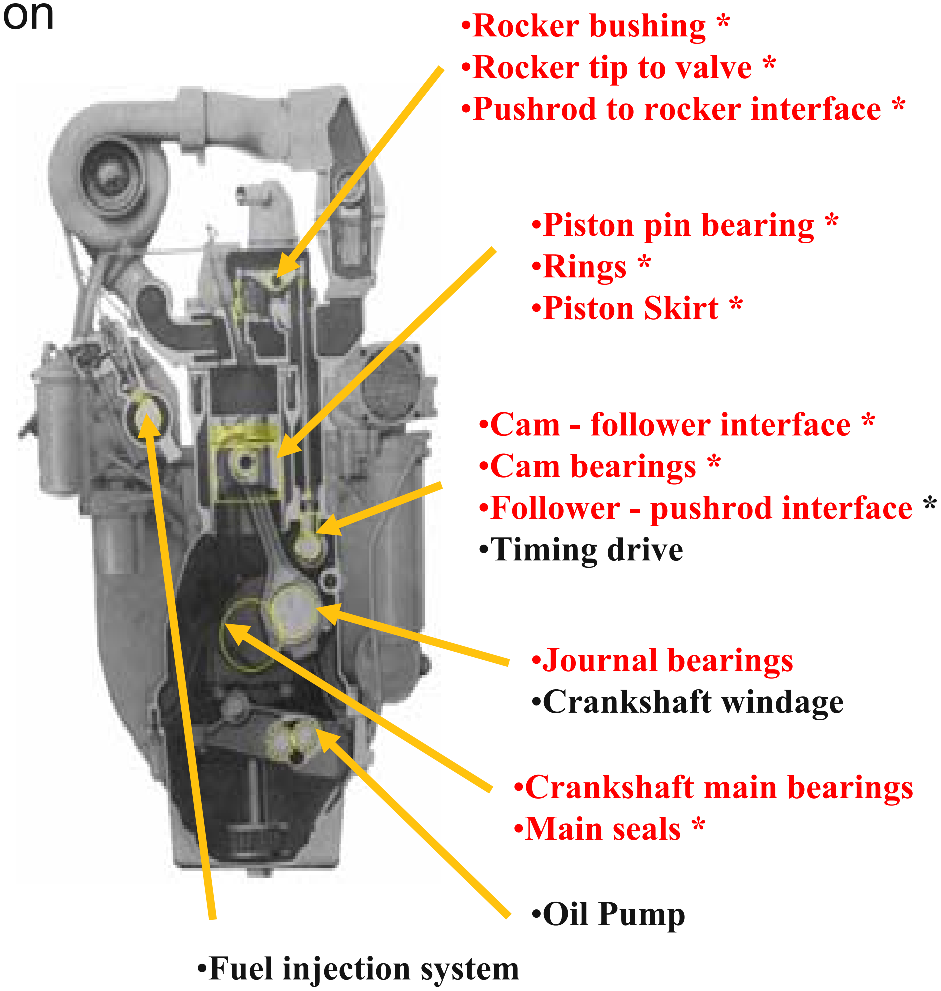
- Different regimes of lubrication depending on the degree of contact between sliding surfaces
- Boundary lubrication characterized by solid-solid contact – asperities of mating surfaces in contact with one another
- Contrast boundary lubrication with full-film lubrication in which mating surfaces are separated by a film.
- In between, mixed lubrication occurs.



ANL/Ricardo Phase I Studies – Identify/Model Frictional Losses in a Diesel Engine & Impact of Lowering Boundary Layer Friction on Fuel Economy

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



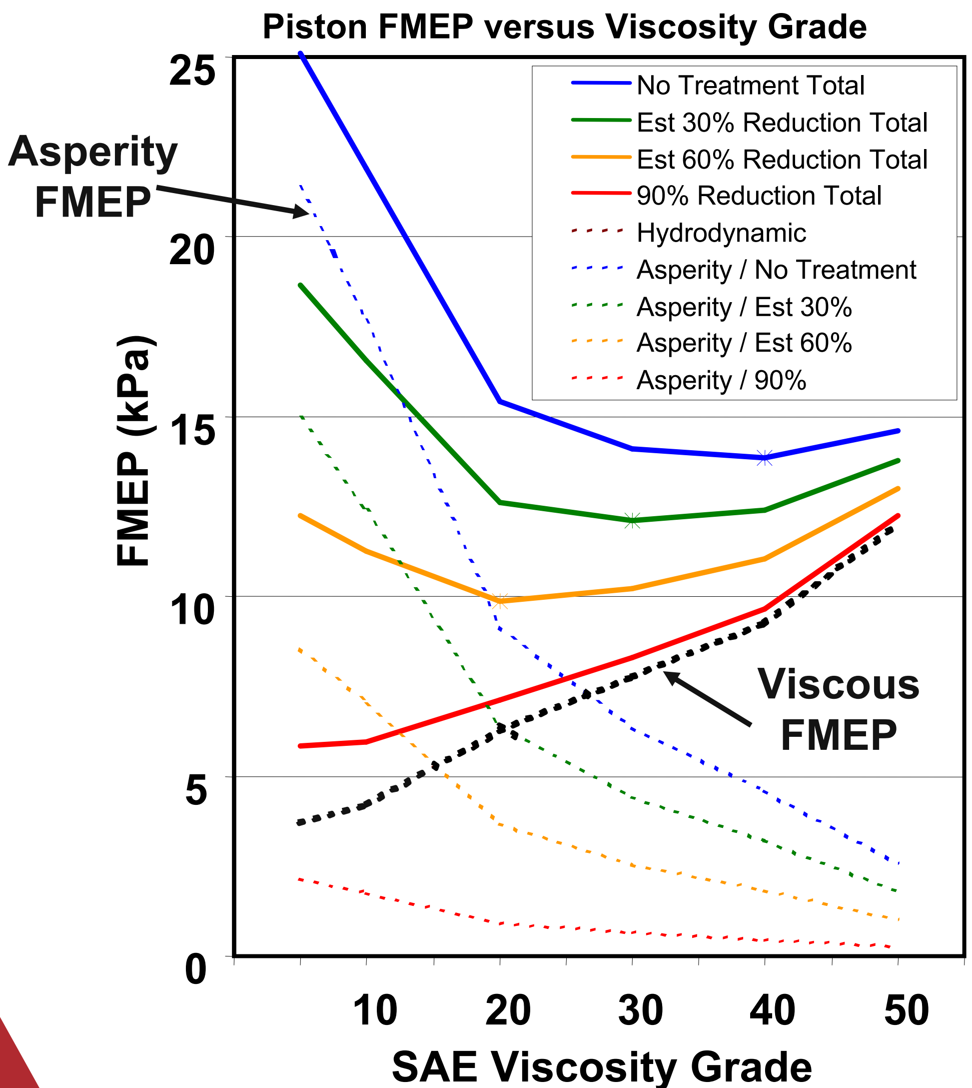


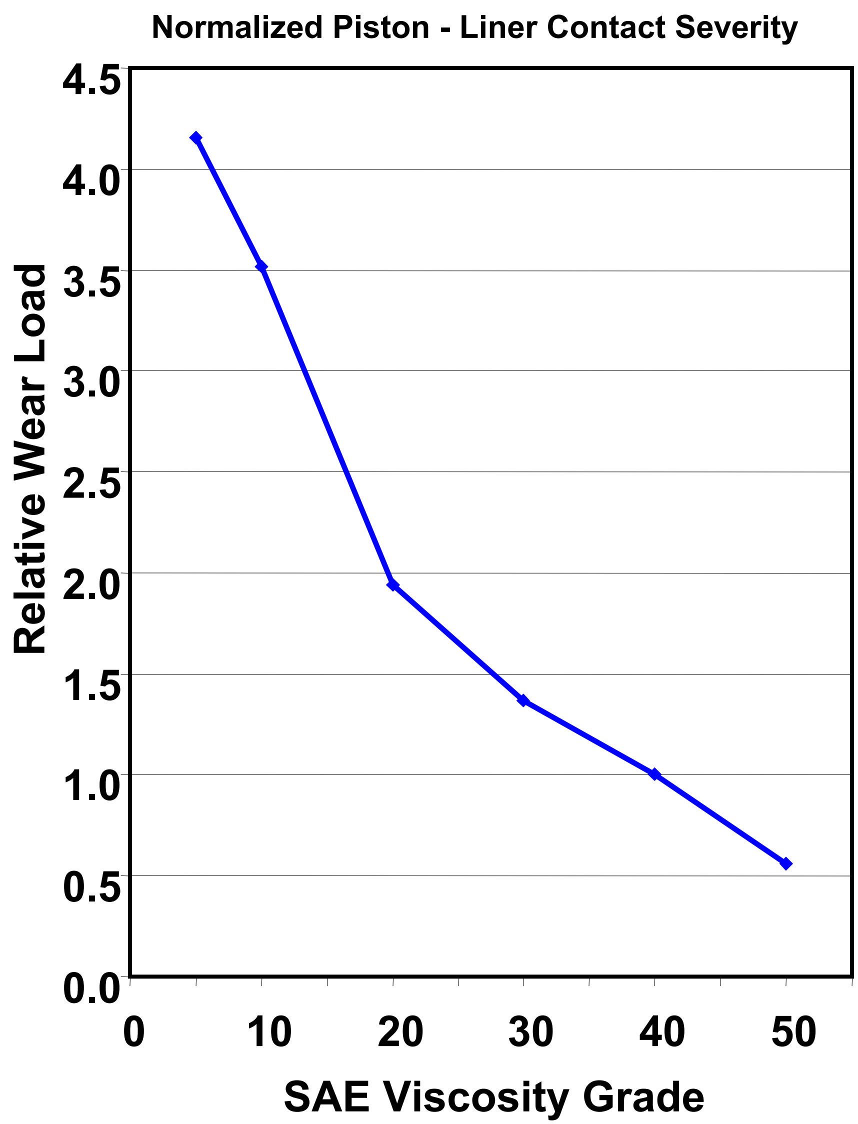
* interface considered in current study

$$\text{FCSF (Fuel Consumption Scaling Factor)} = \frac{\text{IMEP} + \Delta\text{FMEP}}{\text{IMEP}}$$

Boundary and Hydrodynamic Friction: Model Impact on FMEP and Wear Severity

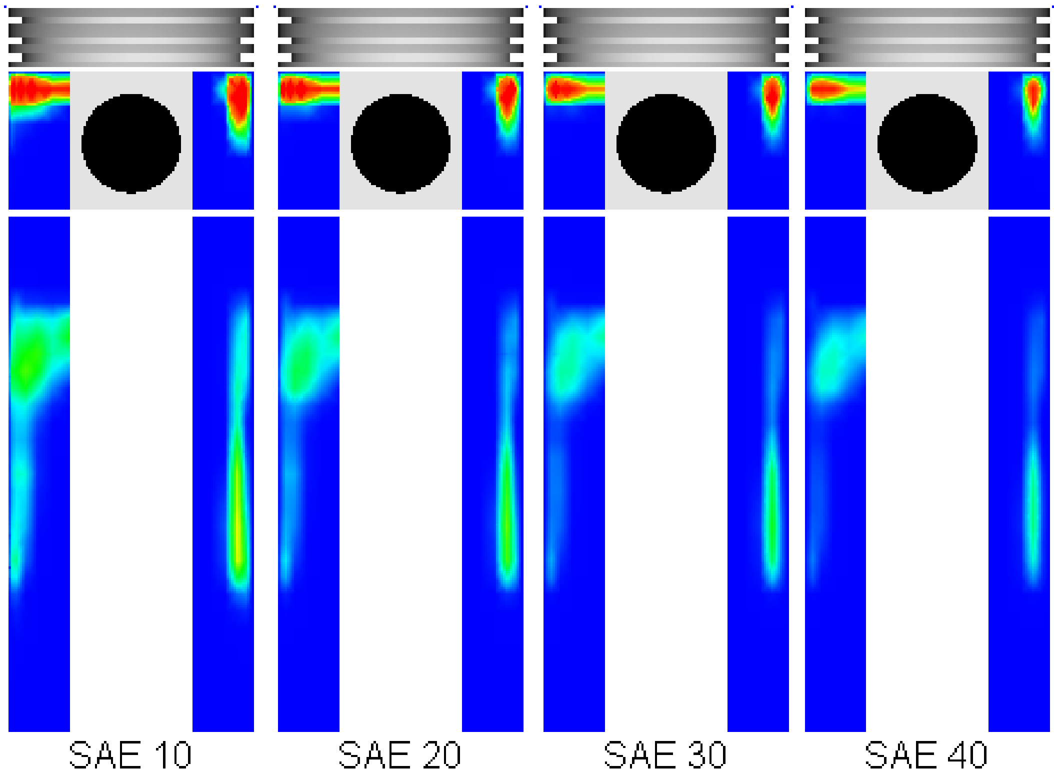
- Total FMEP is the sum of the Asperity friction and the hydrodynamic friction
  - Boundary FMEP decreases with increasing lubricant viscosity – shifting from BL to ML regime
  - Hydrodynamic FMEP increases with increasing viscosity

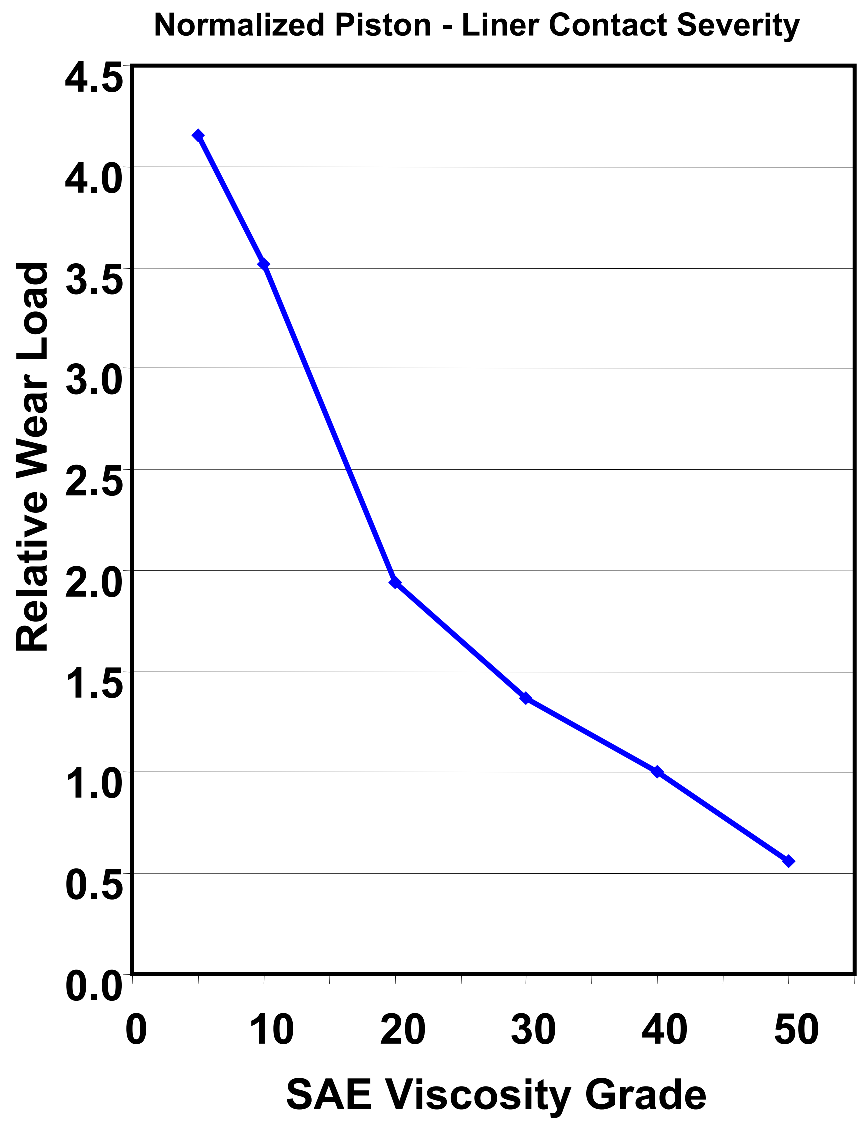




Modeled Contact Severity/Loads – Impact of Low-Viscosity Lubricants on Engine Components

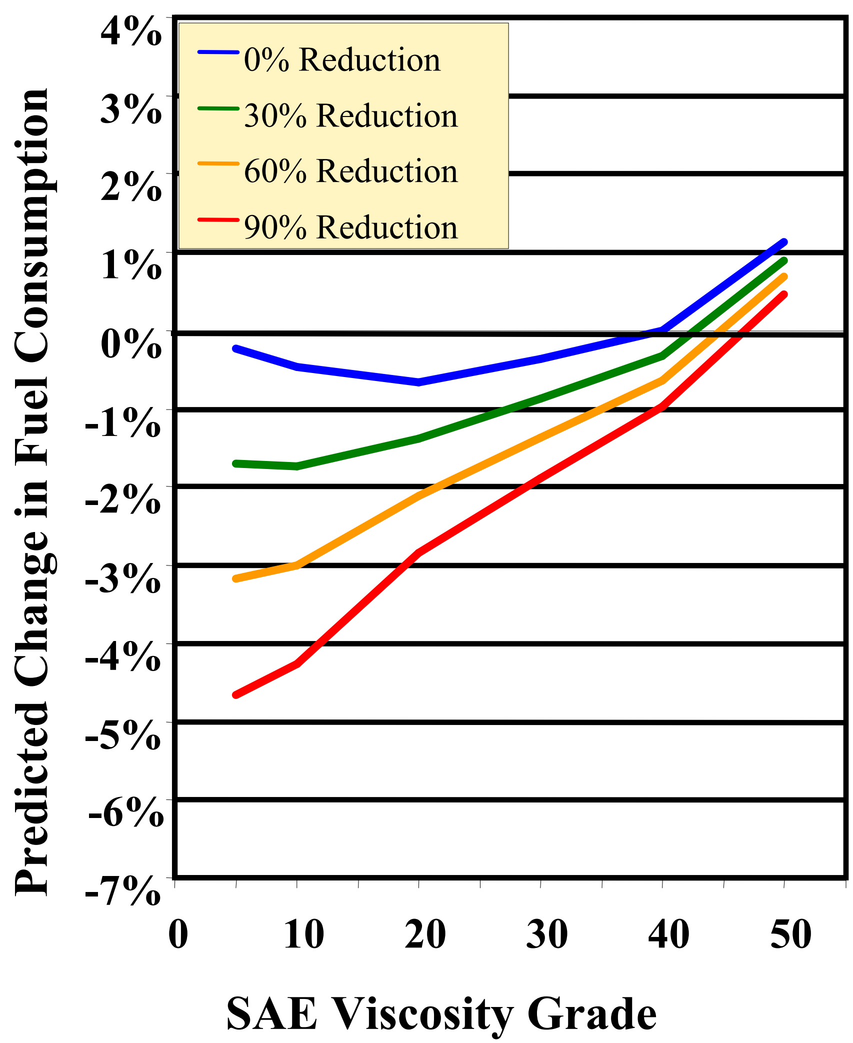
- As lubricant viscosity is reduced, contact between the piston skirt and cylinder liner increases in both magnitude and extent
- Predicted total average contact severity per cycle, using SAE 5 oil, is more than 4 times as high as that using SAE 40 oil
- This model suggests that to allow the use of SAE 5 oil, a surface treatment would have to provide approximately four times the wear resistance of the baseline system, if the wear resistance remained constant over time





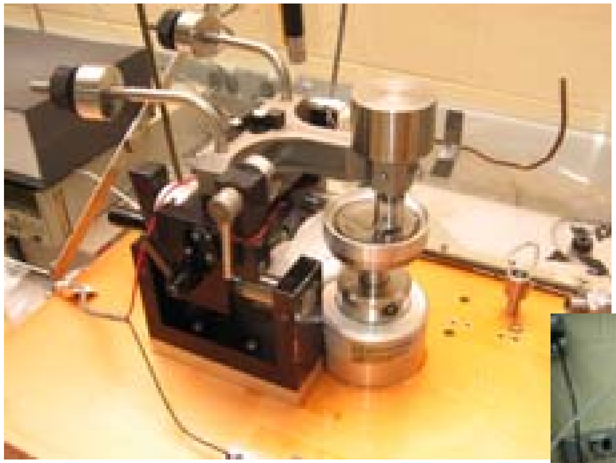
Argonne/Ricardo Phase II Studies – Impact of Reducing Lubricant Viscosity – 3 to 4 % Fuel Savings

- **Reducing only the asperity friction improves fuel economy by 0.4 to 1.3 %**
- **Reducing the boundary layer friction enables the use of a lower-viscosity lubricant**
  - Significant savings possible by combining low friction boundary friction technologies AND low-viscosity lubricants
  - Fuel savings dependent on driving schedule – using low-viscosity lubricants (and low friction surfaces) under driving cycles with high percentages of idling provide significant savings



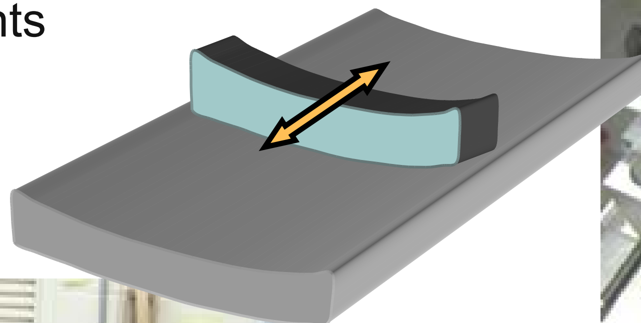
Benchtop Validation of Friction – Can We Achieve 30 to 90% Reductions in Boundary Friction? And How?

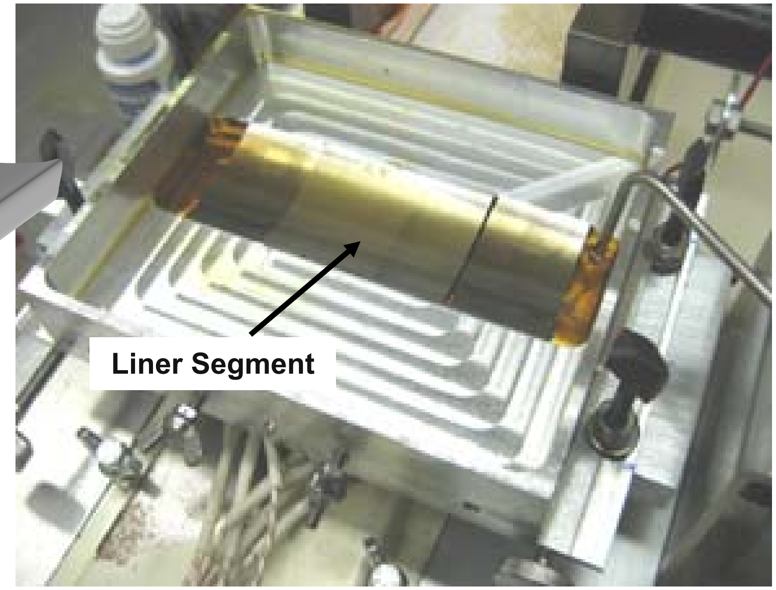
- Measurement of friction using benchtop tribometers providing data on the potential of advanced engineered surfaces and lubricants to provide low-friction tribological systems
  - Candidate low-friction technologies
    - *Coatings (Amorphous carbon, Superhard nanocomposites, Commercial Coatings – CrN, …)*
    - *Lubricants (Additives – formation of low-friction boundary films)*
    - *Textured surfaces*
  - Benchtop test configurations
    - *Unidirectional Sliding*
      - Pin-on-Disc
      - Block-on-Ring
    - *Reciprocating Sliding*
      - Ring-on-Liner

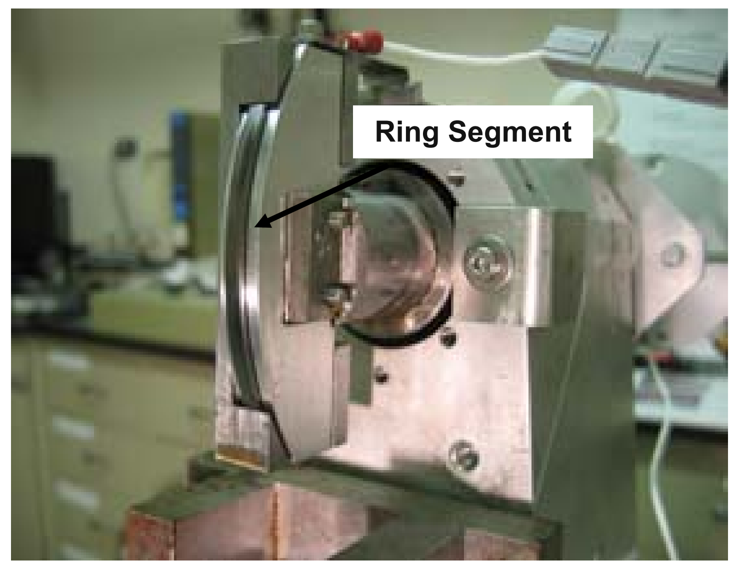


Argonne – Development of a Test Rig to Simulate Ring-Liner Conditions and Evaluate Potential Low-Friction Strategies

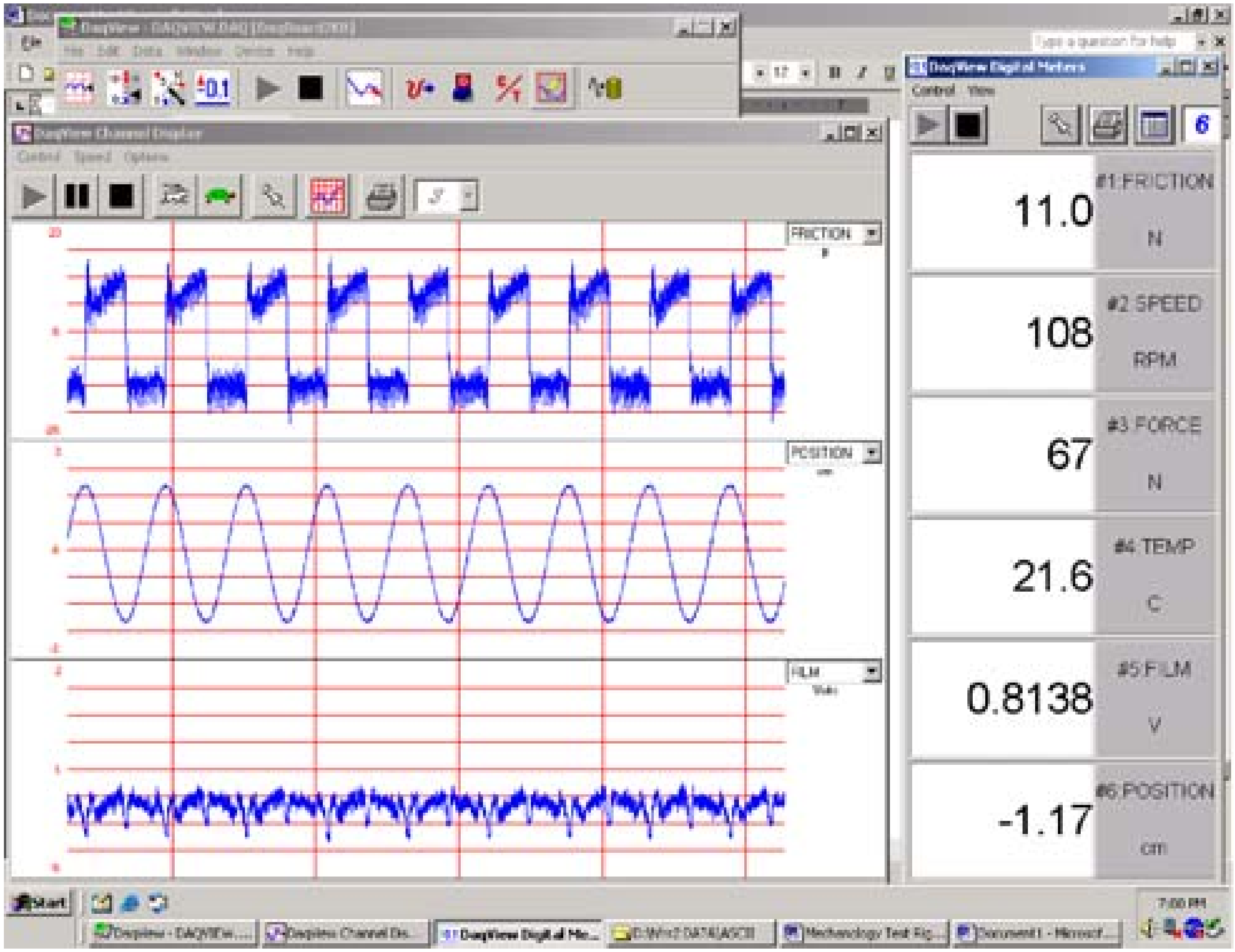
- Modified a Cameron-Plint Rig to operate with prototypic liner segments and ring segments







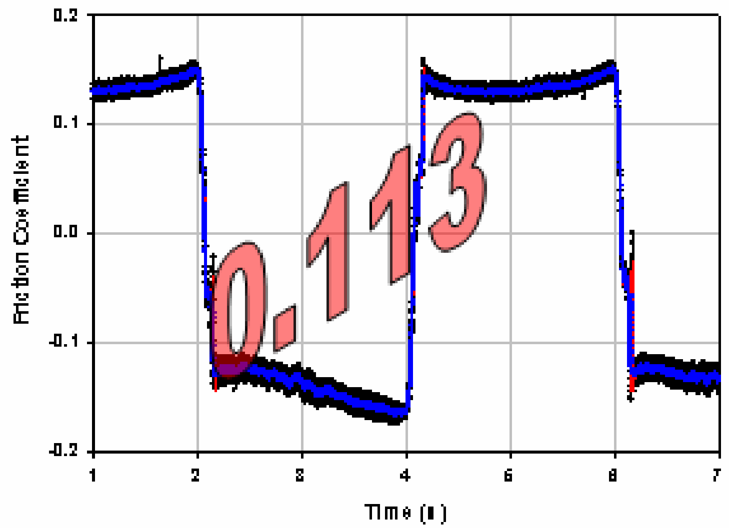
Computer Data Collection

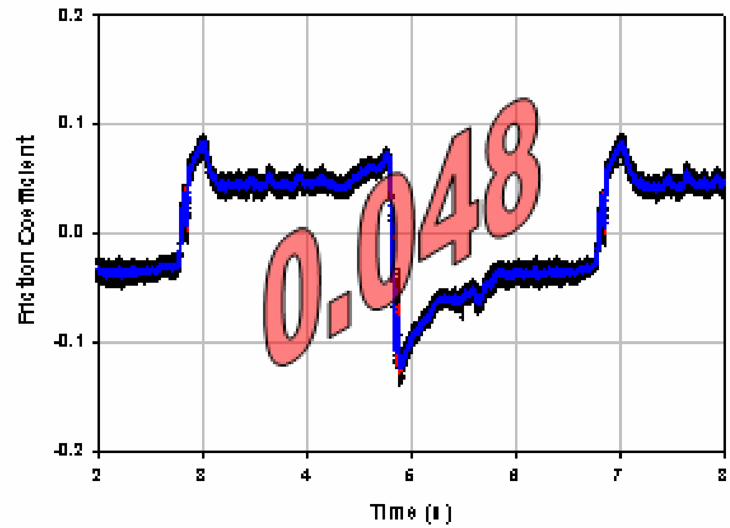


- Measurement of friction, rpm, normal force, instantaneous position, contact resistance, temperature
- Samples Data @ 2 kHz
- Data reduced with Sigmaplot software

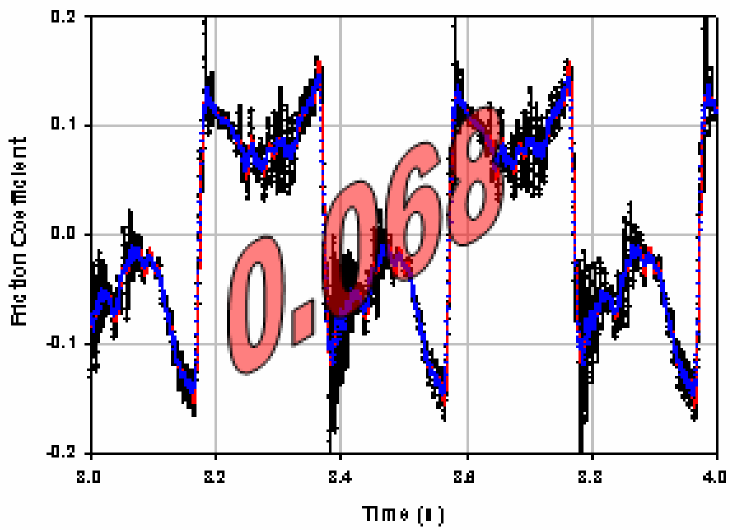
Ring-on-Liner: Lubricant Additive (ROL 060228)

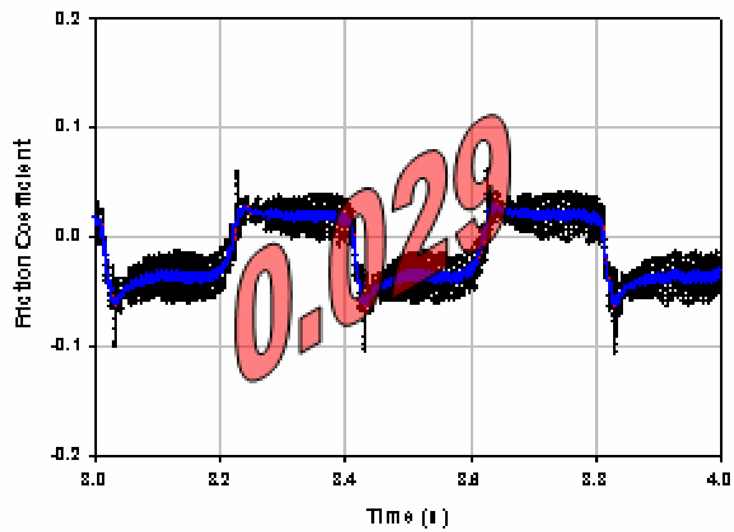
- 10W-30 Synthetic
- Low-Friction Additive





15 rpm

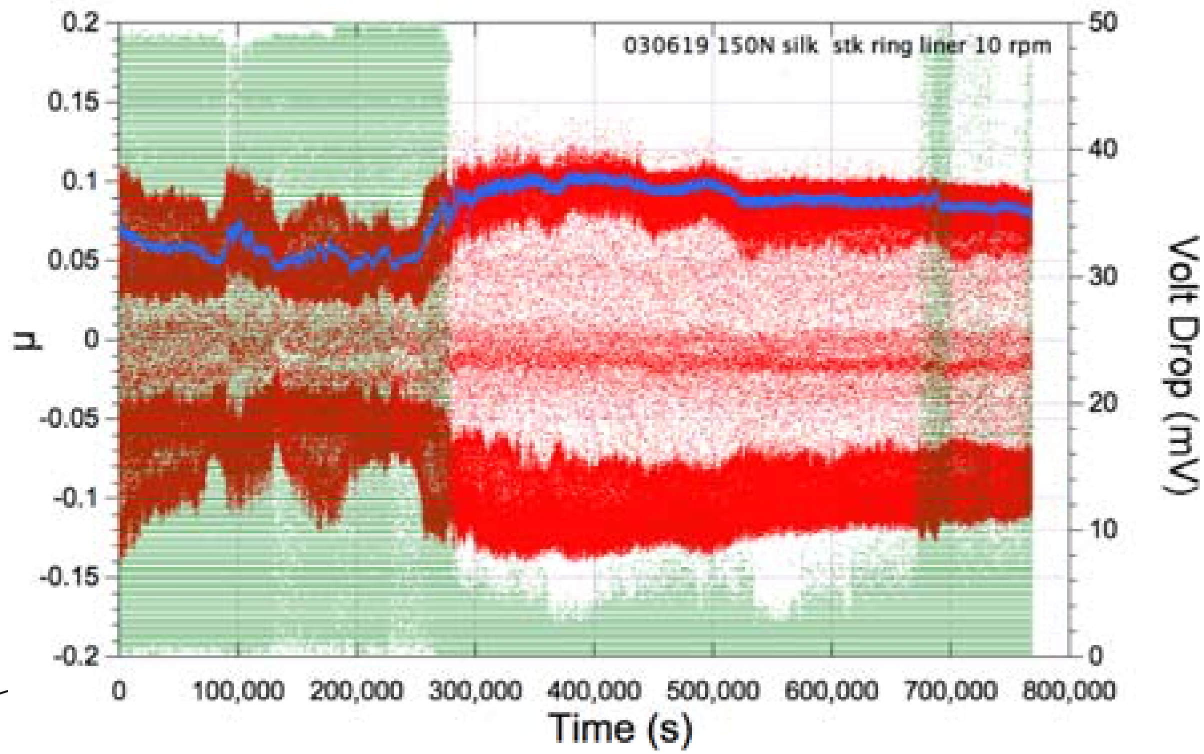


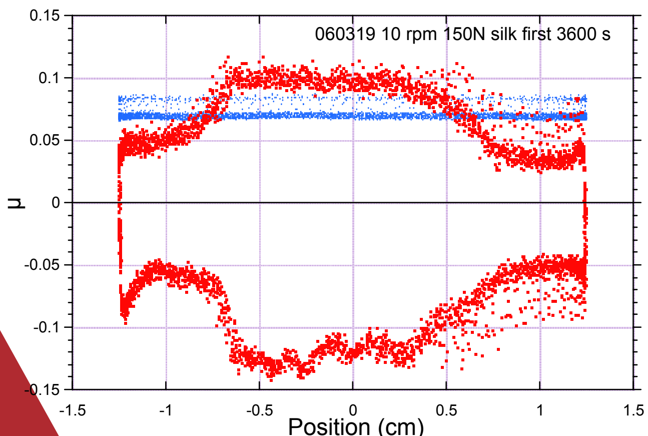


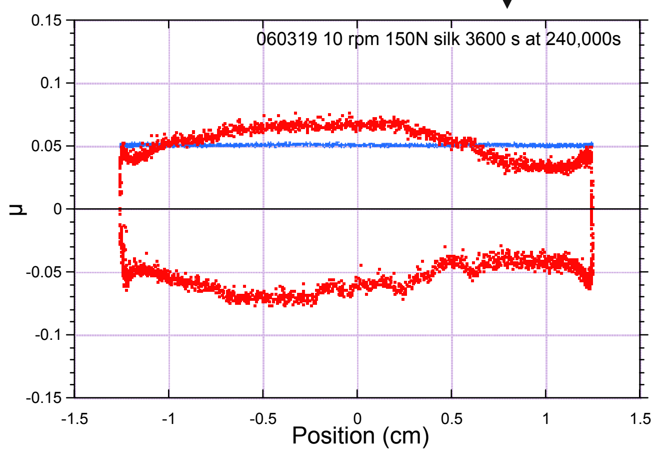
150rpm

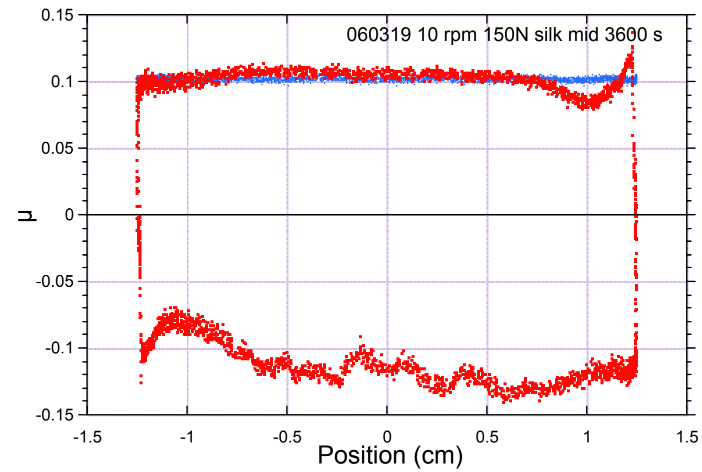
Low-Friction Additive Consumed During 9-Day Benchtop Test

- During extended break-in tests with low-friction additive, the friction was initially low, continued to decrease, then increased as the additive was depleted



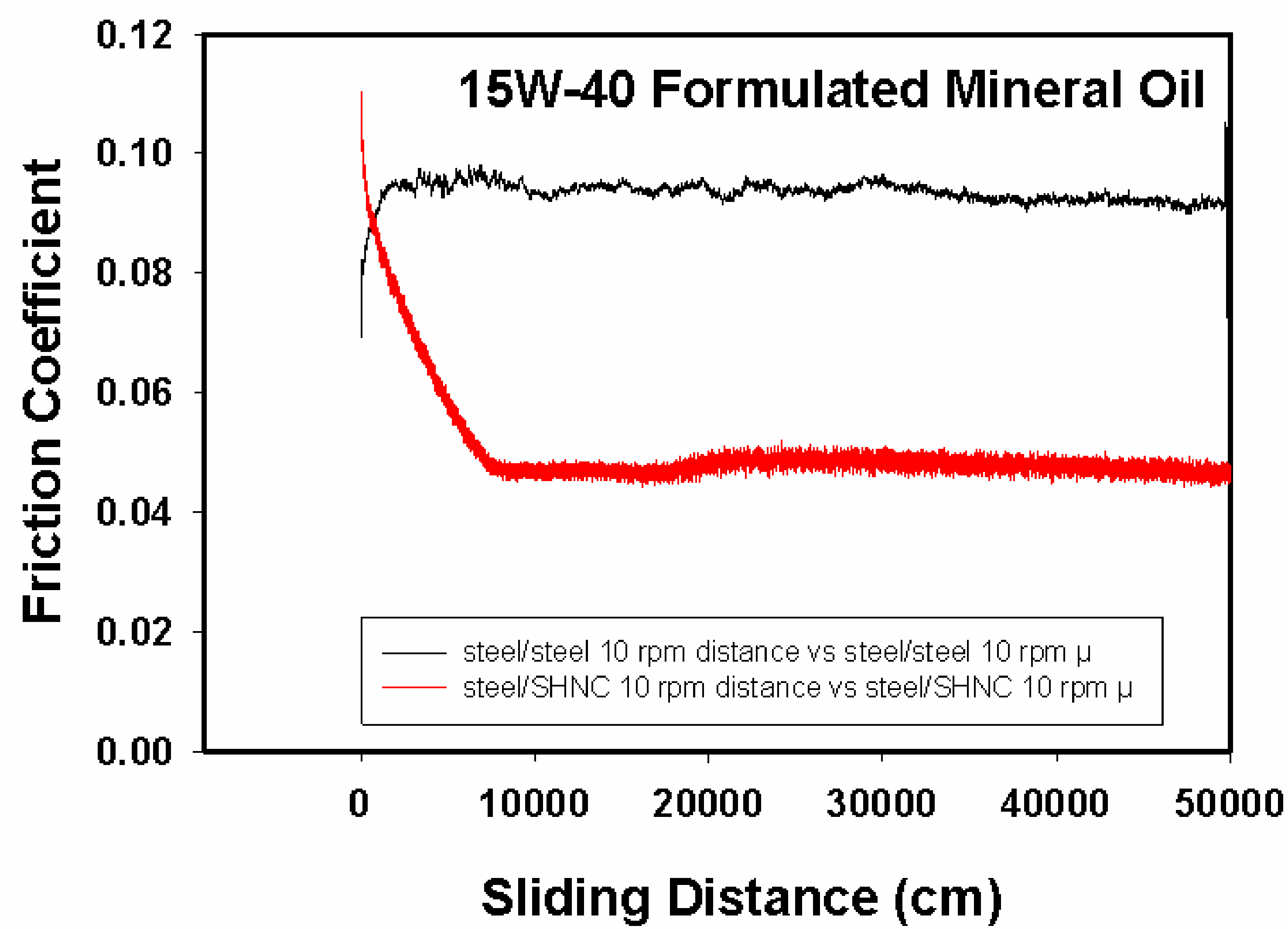






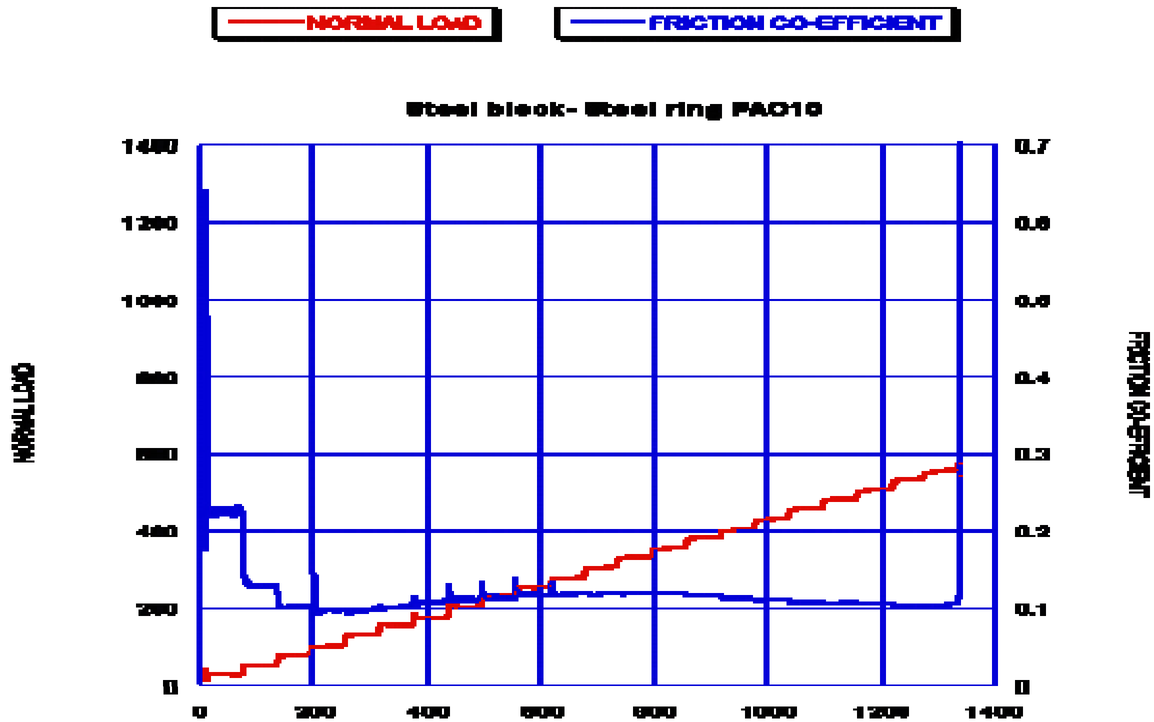
Pin-on-Disc: SuperHard Nanocomposite (More Details To Be Presented by Ali Erdemir)

- Room temperature pin-on-disc friction studies of steel ball sliding against steel disc or Superhard Nanocomposite, low-friction coatings – 50 % reduction in friction

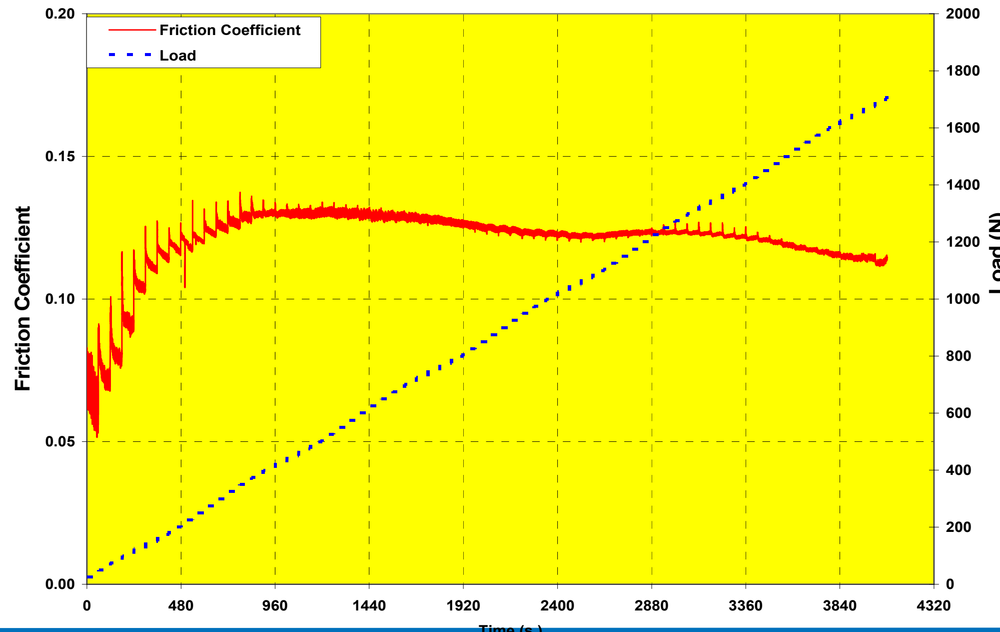


Block-on-Ring: Scuffing Performance (More Details To Be Presented by Ajayi/Erdemir)

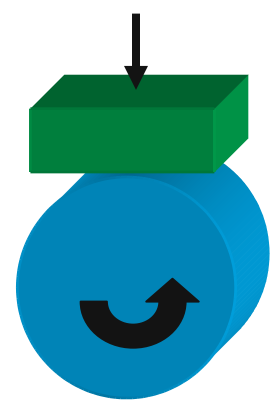
Steel/Steel
600 N scuffing load



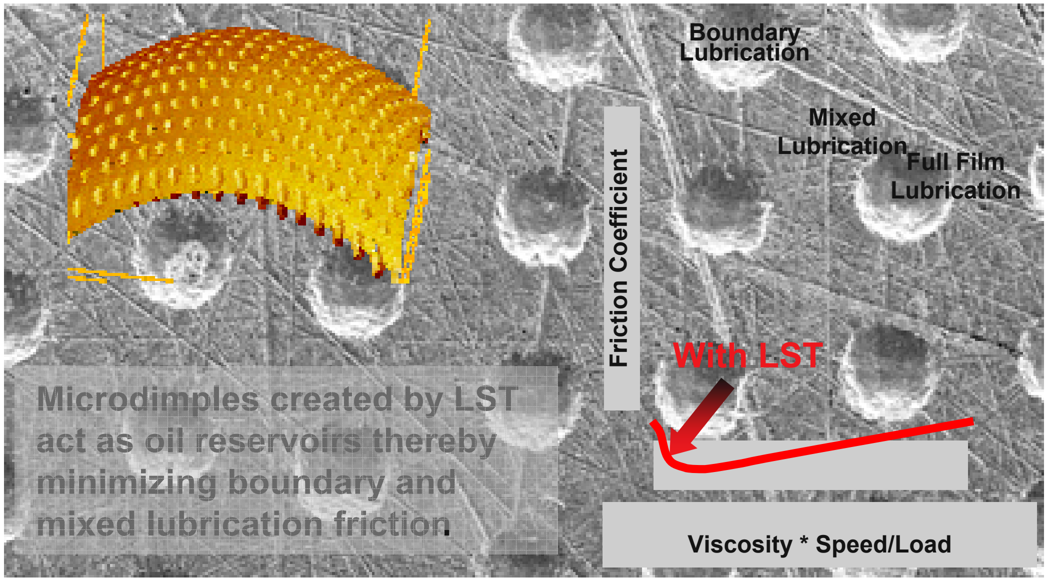
SHNC/SHNC
>1700 N scuffing load



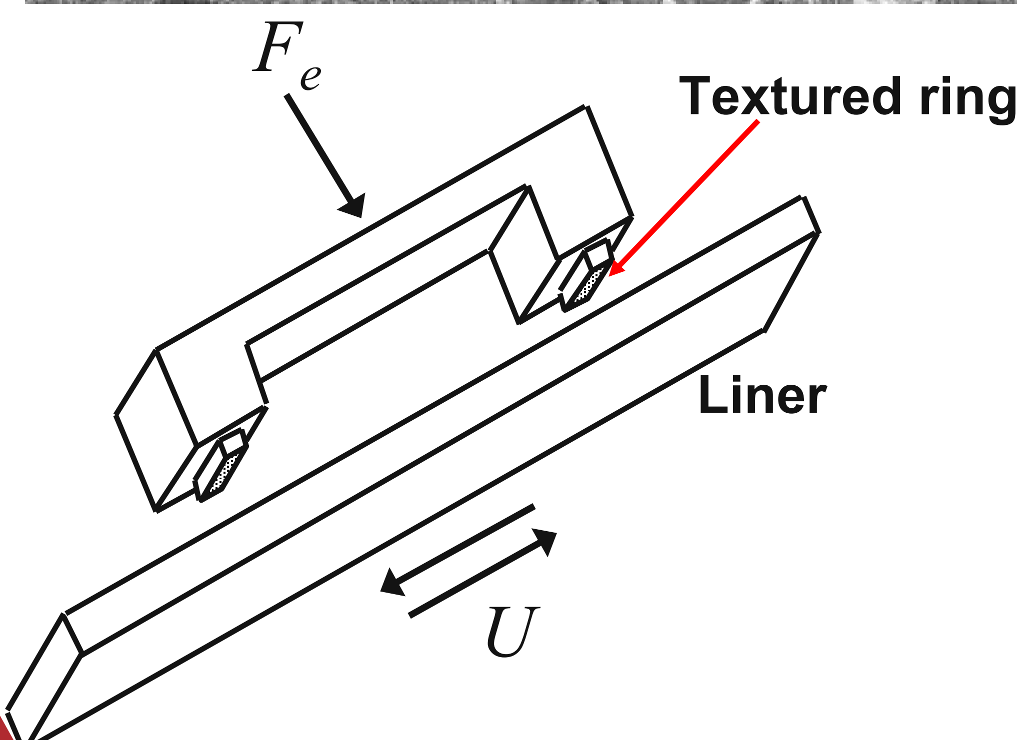
- Operation with low-viscosity fluids raises concerns with regard to scuffing. Can we identify coating and/or additive systems that have improved scuffing resistance?
  - Block-on-ring configuration is used to evaluate scuff resistance

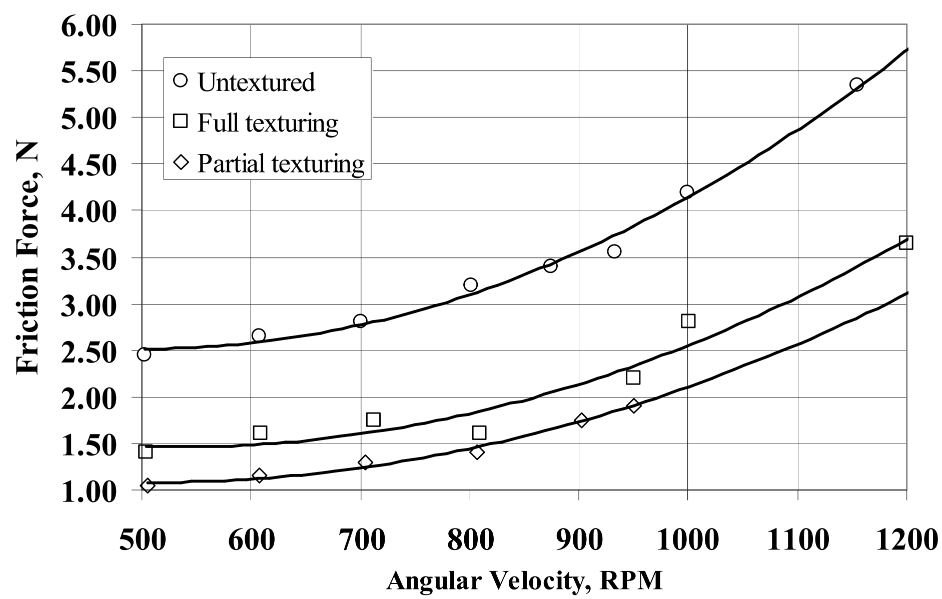


Textured Surfaces as a Method to Reduce Hydrodynamic and Mixed Lubrication Friction



- Argonne (in collaboration with Technion University – Prof. I. Etsion) is evaluating the potential of laser surface texturing to reduce friction on engineered surfaces
- Results suggest LST may provide significant energy savings regimes where **conformal contact** is present





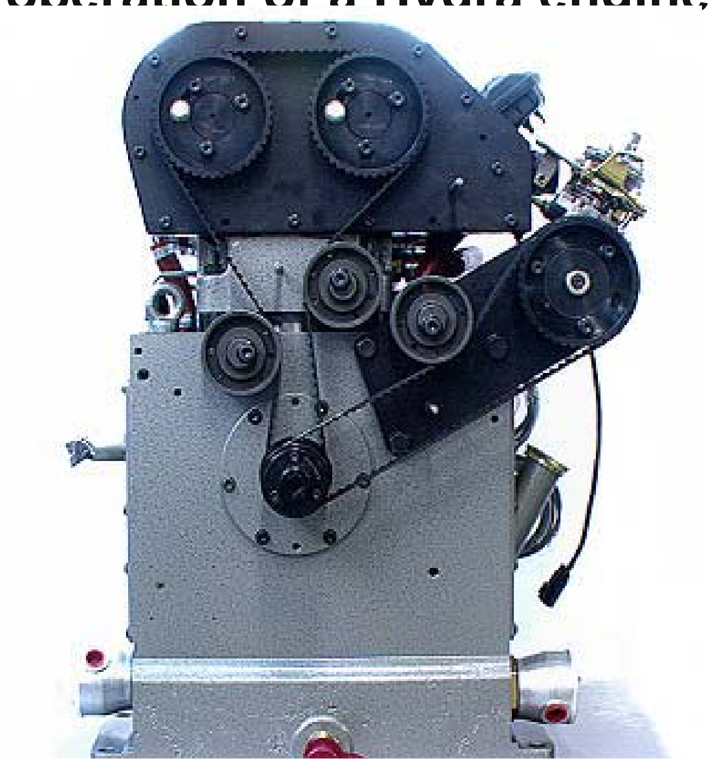
Fired, Single-Cylinder Diesel Tests: Ricardo/U-Mich – Phase III – Validate Models and Low-Friction Technologies

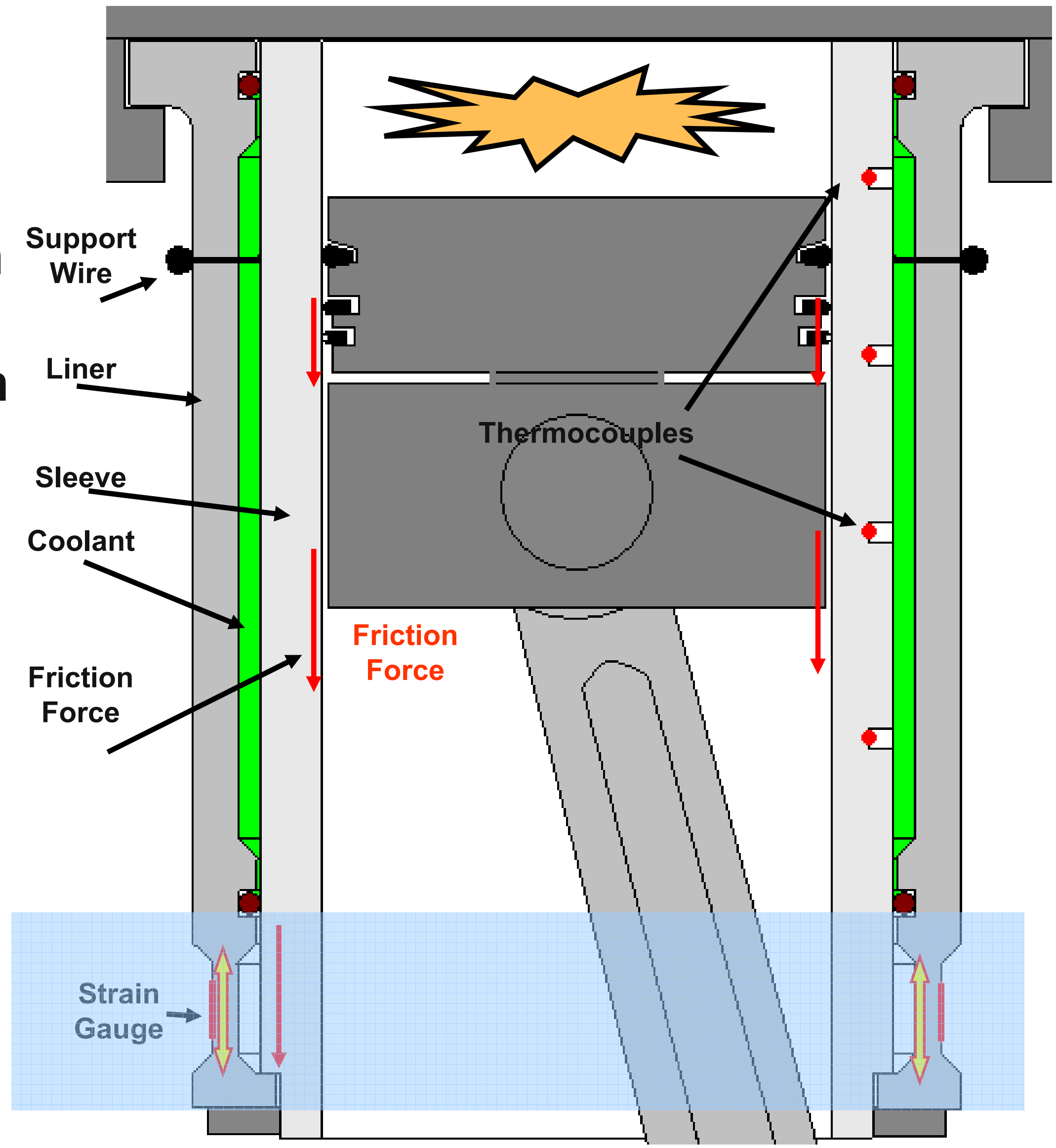
- Validate model predictions and low-friction technologies

- Ricardo examined multiple approaches to validate fuel economy predictions
  - Direct fuel consumption, instrumented multi-cylinder engine, instrumented single-cylinder diesel engine, motored engine, …
- Selected Approach (Instrumented, Single-Cylinder Hydra Engine) :
  - Modify an existing single-cylinder test engine for friction measurement, using the fixed-sleeve approach
  - Run the engine with a variety of lubricants, with and without NFC coatings at each of the interfaces
  - Measure instantaneous friction at these interfaces
  - Calculate the change in asperity friction coefficients due to the application of the coatings
  - Use the experimentally-derived friction coefficient improvements to refine the earlier estimates of fuel economy improvement over the FTP HD test cycle

Ricardo/U-Mich – Modifications to Hydra Engine for in-situ Friction Force Measurements

- Ricardo has been producing single cylinder engines for research and development since 1919
- A number of standard conversion kits exist to extend the range of operation of a Hydra engine, such





Proposed Test Matrix

- **The following combinations of engine build, load condition, and lubricant will be tested:**

Engine Configurations	Oil Viscosity	Operating Conditions	Data Collected
Baseline – Stock ring and Liner	SAE 40	Partial Load 1 Partial Load 2 Full Load	Cylinder Pressure Oil Sump Temperature Coolant Temperature Liner temperature Profile Friction Force Engine Blow-By Gas Flow
	SAE 20		
Low Friction Ring and/or Piston	SAE 40	Partial Load 1 Partial Load 2 Full Load	
	SAE 20		
Lubricant Additive (s))	SAE 40	Partial Load 1 Partial Load 2 Full Load	
	SAE 20		
Low-Friction Ring & Liner	SAE 40	Partial Load 1 Partial Load 2 Full Load	
	SAE 20		

Summary/Conclusions

- A series of mechanistic models have been developed and integrated into a suite of codes capable of predicting parasitic energy losses in a heavy duty diesel engine
- The code predicts the impact of the tribological environment on the FMEP and fuel consumption by appropriate application of weighting factors applied to calculations at 8 engine load/speed modes
- Fuel consumption savings up to 3-4 % are predicted through a combination of low viscosity engine lubricants coupled with low-friction surfaces
- Benchtop friction tests are being employed to identify potential technologies/approaches to achieve levels of friction reductions required to improve fuel economy and to determine the conditions necessary to achieve reduced friction
  - Additives, coatings, and surface texturing
- Modifications to a fired, single-cylinder diesel engine are in progress to provide in-situ friction measurements of baseline and advanced low-friction components and to validate the mechanistic models

Future Activities:

- Single-Cylinder, Fired Diesel Tests with in-situ measurement of ring/piston – liner friction forces
  - Effect of viscosity, low friction coatings, and additives
- Multi-cylinder engine and/or fleet studies
  - Fuel efficiency and system durability

- PSAT integration
  - Development of PSAT modules to incorporate mechanistic models into vehicle system efficiency studies
- Auxiliaries
  - Parasitic energy losses in auxiliary systems
    - *Fluid pumps (fuel, oil, water) are often oversized to accommodate degradation/wear over the system lifetime.*
    - *Compressors*
    - *Cooling fan, alternator, steering*
- Transmissions and axles (Eaton/Caterpillar/ANL/NWU)

Closing Remarks ……

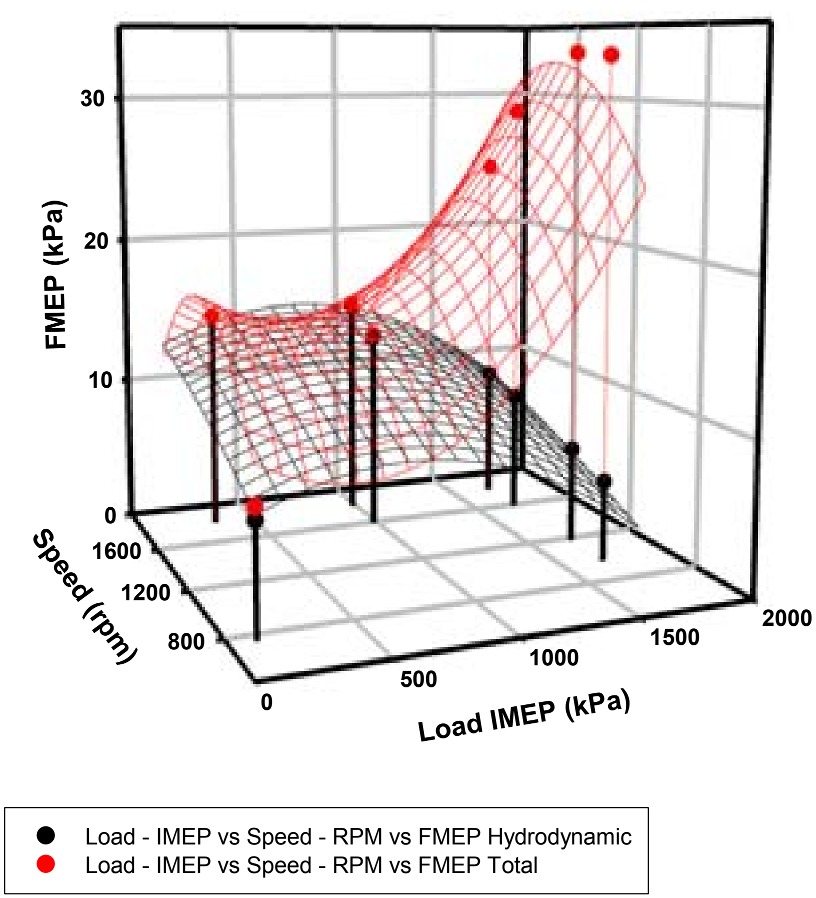
Application of Mechanistic Models to Vehicle System Optimization – Component Optimization & Vehicle Optimization (PSAT)

- Develop 'look-up' tables/regressions for use in PSAT Vehicle Simulation Software

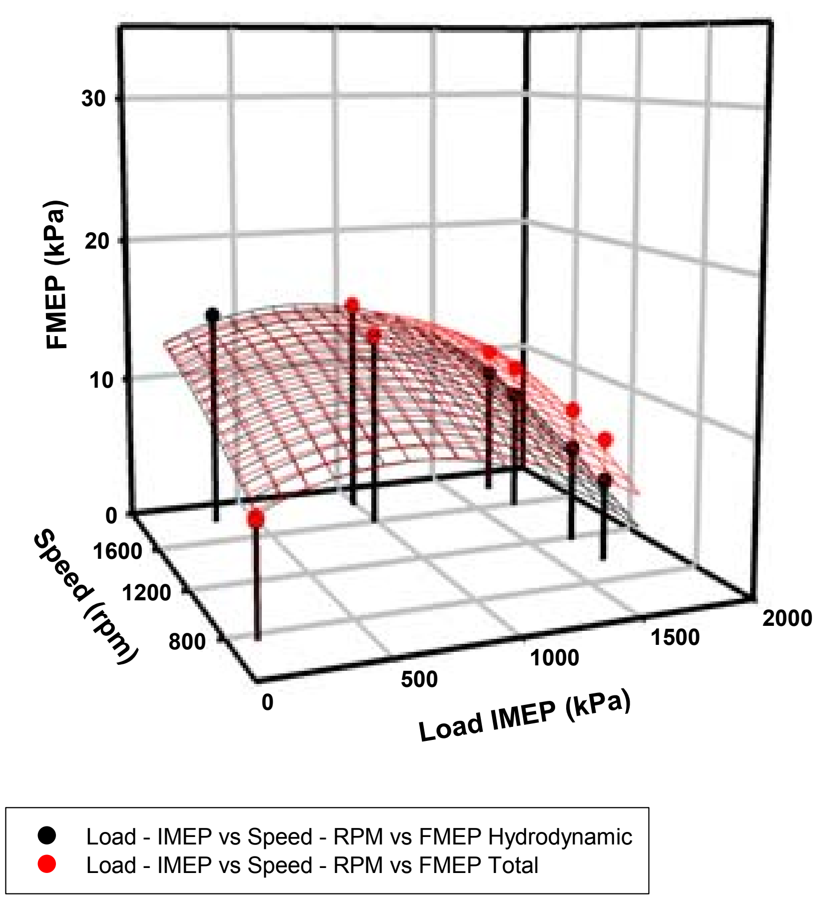
$$\text{FCSF} = \frac{\text{IMEP} + \Delta\text{FMEP}}{\text{IMEP}}$$

(Fuel Consumption Scaling Factor)

Piston Skirt FMEP
Baseline BLL Friction
SAE 40

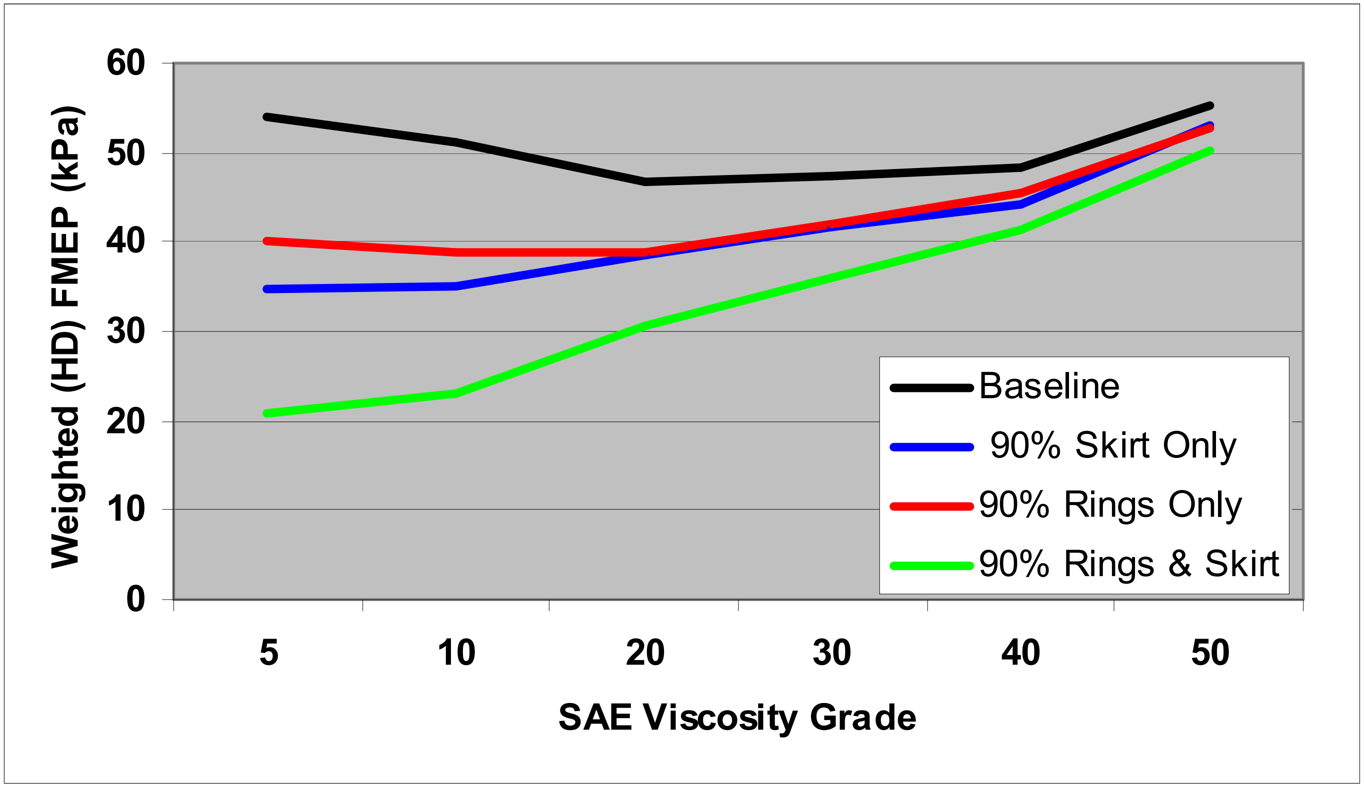


Piston Skirt FMEP
90% BLL Friction Reduction
SAE 40



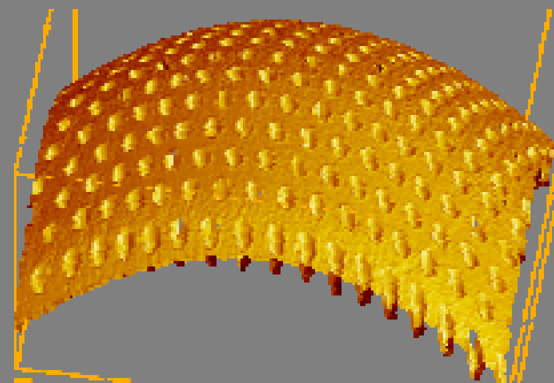
Which Components Have the Biggest Impact – What Should be Treated?

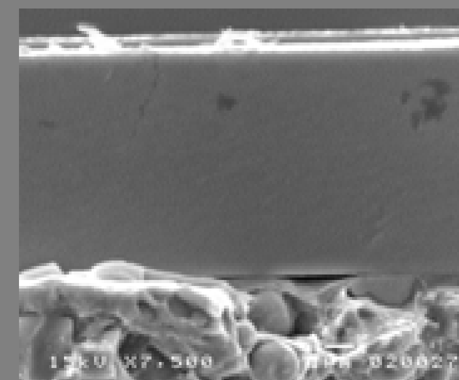
- Approach can be extended to consider treating a few select components with variable friction reductions
  - Do you treat only the skirt, only the rings, or both?? A low-friction treatment (e.g. coating) applied only to the rings is not much different from treating only the skirt. Treating both rings and skirt helps at low viscosities.
  - Alternatively can one identify an additive that effectively works on all surfaces
  - Can one tailor the surface chemistry of select components for enhanced lubrication



Benchtop Studies – What Is the Magnitude of Friction Savings That Can be Achieved, and What Level of Increased Protection

- **Models assumed 30, 60, and 90% reductions in boundary friction – what are realistic friction coefficients, how do they compare to the baseline assumptions – are there technologies that can provide these levels of improvements**

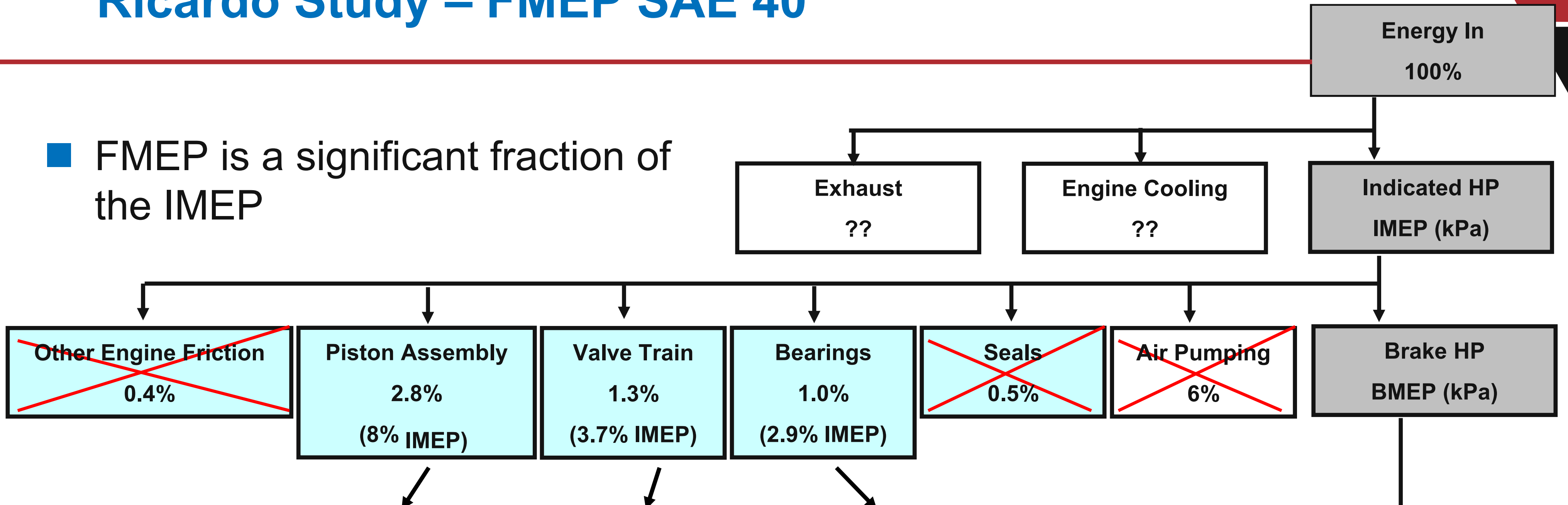


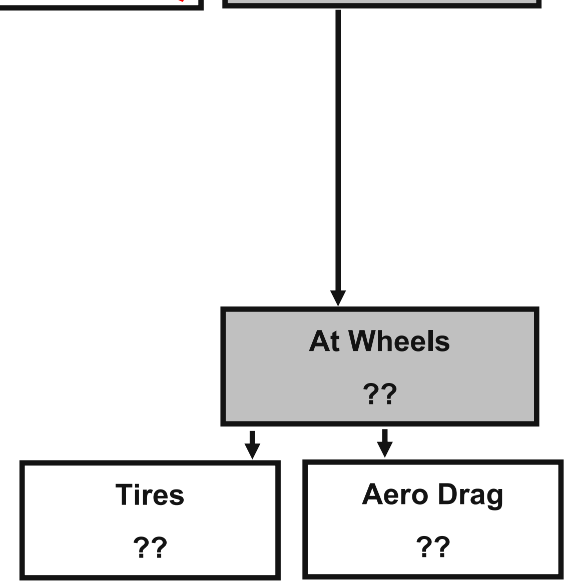


- **Pin-on-Disc, Reciprocating, Block-on-Ring, and Ring-on-Liner Configurations**
  - Friction, Wear, Scuffing-Resistance of test coupons and prototypic rings and liner segments
- **Coatings, Surface Texturing, and Additives**

Ricardo Study – FMEP SAE 40

- FMEP is a significant fraction of the IMEP





Mode Rpm/kPa	Piston FMEP		Valvetrain FMEP		Bearings FMEP	
	Viscous (kPa)	Asperity (kPa)	Viscous (kPa)	Asperity (kPa)	Viscous (kPa)	Asperity (kPa)
1) 750/104	**29.7**	**5.2**	**0**	**4.6**	**12.3**	**10.15**
2) 960/1683	**2.1**	**1.9**	**0**	**0.2**	**1.14**	**0.02**
3) 1170/1683	**2.4**	**1.8**	**0**	**0.2**	**1.34**	**0.02**
4) 1590/983	**5.4**	**0.2**	**0**	**0.2**	**2.64**	**0.01**
5) 1590/1683	**3.0**	**1.3**	**0**	**0.1**	**1.73**	**0.01**
6) 1800/325	**16.9**	**0.4**	**0**	**0.6**	**7.93**	**0.0**
7) 1800/983	**5.8**	**0.1**	**0**	**0.2**	**2.81**	**0.0**
8) 1800/1683	**3.2**	**1.0**	**0**	**0.1**	**1.82**	**0.01**
Weighted Average	48.4 kPa 7.8% <IMEP>		3.6 kPa 0.6% <IMEP>		19.4 kPA 3.1% <IMEP>	

← **11.5% of IMEP**

Ricardo Study – FMEP SAE 20 & 90 % Asperity Reduction

- **FMEP is a significant fraction of the IMEP**

Energy In
100%

Exhaust
??

Engine Cooling
??

Indicated HP
IMEP (kPa)

Other Engine Friction
0.4%

Piston Assembly
2.8%
(8% IMEP)

Valve Train
1.3%
(3.7% IMEP)

Bearings
1.0%
(2.9% IMEP)

Seals
0.5%

Air Pumping
6%

Brake HP
BMEP (kPa)

At Wheels
??

Tires
??

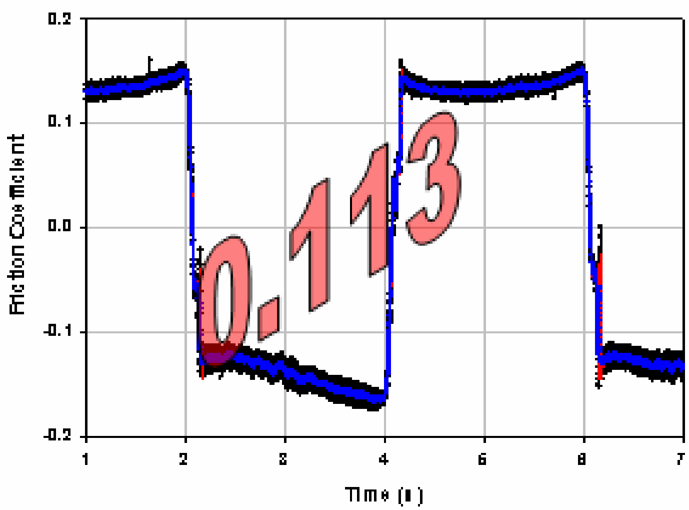
Aero Drag
??

Mode Rpm/kPa	Piston FMEP		Valvetrain FMEP		Bearings FMEP	
	Viscous (kPa)	Asperity (kPa)	Viscous (kPa)	Asperity (kPa)	Viscous (kPa)	Asperity (kPa)
1) 750/104	**20.58**	**0.73**	**0**	**1.591**	**10.2**	**0.026**
2) 960/1683	**1.52**	**0.01**	**0**	**0.004**	**1.0**	**0.013**
3) 1170/1683	**1.75**	**0.012**	**0**	**0.004**	**1.2**	**0.004**
4) 1590/983	**3.81**	**0.009**	**0**	**0.023**	**2.3**	**0.002**
5) 1590/1683	**2.17**	**0.019**	**0**	**0.006**	**1.5**	**0.002**
6) 1800/325	**12.14**	**0.008**	**0**	**0.025**	**7.2**	**0.000**
7) 1800/983	**4.14**	**0.004**	**0**	**0.011**	**2.5**	**0.000**
8) 1800/1683	**2.32**	**0.009**	**0**	**0.004**	**1.6**	**0.001**
Weighted Average	30.6 kPA 5% <IMEP>		2.4 kPa 0.4% <IMEP>		16.8 kPa 2.7% <IMEP>	

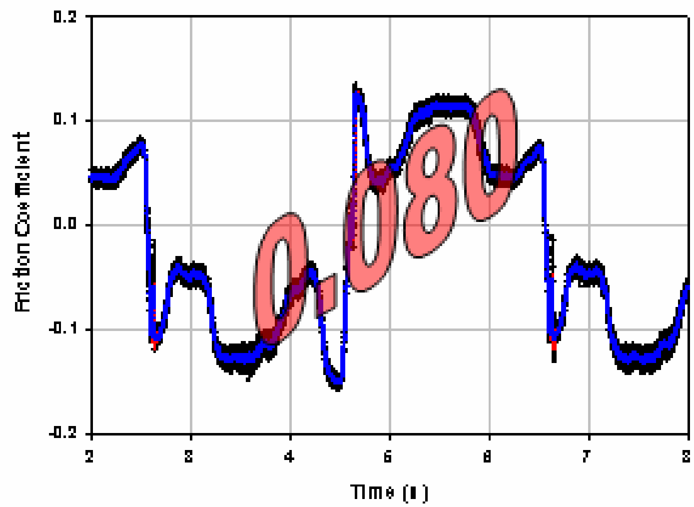
8.1% of IMEP

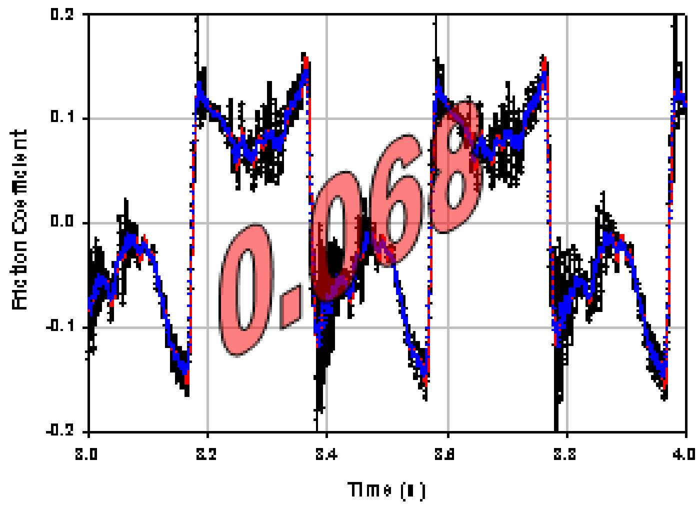
Ring-on-Liner: Lubricant Additive (ROL 060228)

- 10W-30 Synthetic
- Low-Friction Additive



15 rpm





150rpm