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Boundary Layer Lubrication

Oyelayo O. Ajayi
Argonne National Laboratory

Sponsored by Lee Slezak
Heavy Vehicle System Optimization

<u>Team members</u>
Cinta Lorenzo-Martin
Robert Erck
George Fenske
Jules Routbort
Ali Erdemir
Osman Eryilmaz

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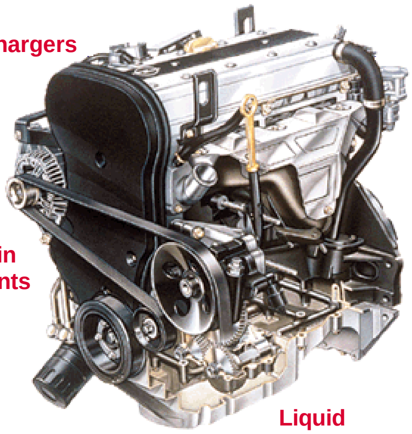
Impact of Friction Reduction on Vehicle Efficiency

- Friction reduction by effective lubrication can translate to significant Fuel savings

- Analysis shows possible efficiency gain by friction reduction - > 5%
  - *Translates to 1200 M gallon of diesel fuel saving per year (about 240 M gallon saving/% efficiency gain)*



Engine - >4%

Axle – 2%

Transmission - 3%

Higher Power Density and Size Reduction

- Components and system power density increase will lead to significant increase in efficiency
  - Size and weight reduction
  - 5 – 15 % fuel savings possible

  (significant annual fuel savings)

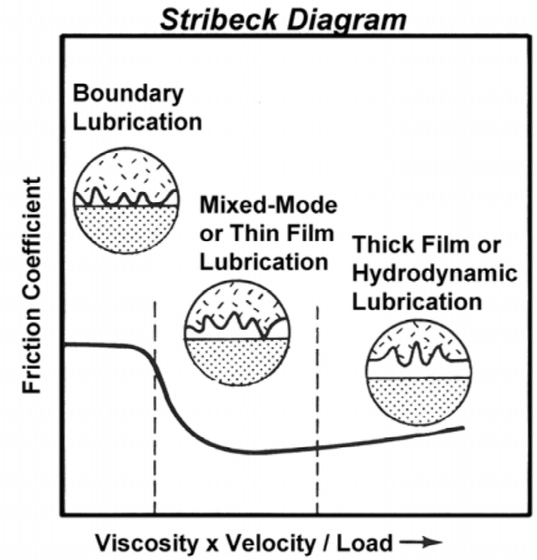
- Power density increase leads to higher contact severity
  - Component may operate mostly under boundary lubrication
  - Exceed material capability – failure

Purpose of Work and Justification for Project

- Achieving sustainable friction reduction and scuffing prevention with increasing power density requires better understanding of boundary lubrication

Boundary lubrication is complex:
–Poor understanding of chemical films and near-surface material behavior

Biggest payoff in terms of friction reduction is in the boundary regime.



<u>Goal:</u> Develop better understanding of boundary lubrication mechanisms and the failures therein using a system engineering approach.

Benefits

- Improve efficiency of exiting systems and components
  - Predictable friction reduction
- Facilitate effective new lubricant formulation for friction reduction and non-ferrous surfaces
- Facilitate development of smaller, more efficeint high power density systems and components
  - Without sacrificing reliability and durability
- Applicable to ALL heavy vehicles regardless of powersource or fuel.

Approach: System Engineering

Project Plan and Structure

Materials

Near-surface-material dynamic changes: - scuffing

Basic mechanism of scuffing failure
Prediction and prevention

Role of surface modification:
- coatings

Chemical Films

Boundary film formation and loss rate:
- APS, other surface analysis tools

Mechanical and friction properties of boundary films measurement

Models for film formation, mechanical and frictional behavior

Integrate both elements with EHD to formulate failure/performance prediction methodology for lubricated components

Technical Accomplishments to Date

- Extensive characterization of the dynamics of near surface material changes during scuffing process by cross-sectional microscopy

- Developed and validated a scuffing model for metallic materials:
  - Scuffing initiates by adiabatic shear instability – can predict shear strain required for scuffing initiation

$$\gamma = \frac{n\rho C_v}{0.9\frac{\partial\tau}{\partial T}}$$

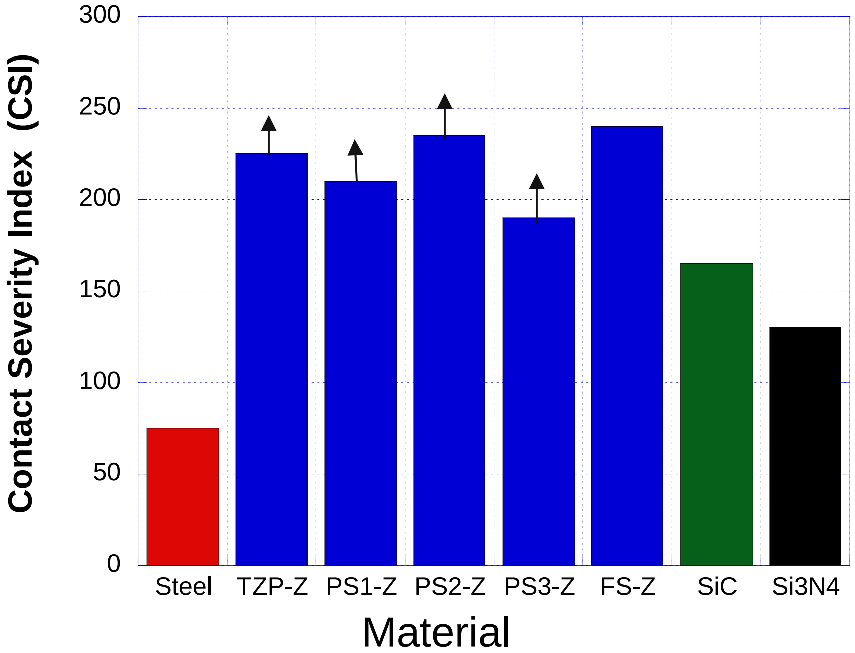
  - Scuffing propagates by contact interface heat management

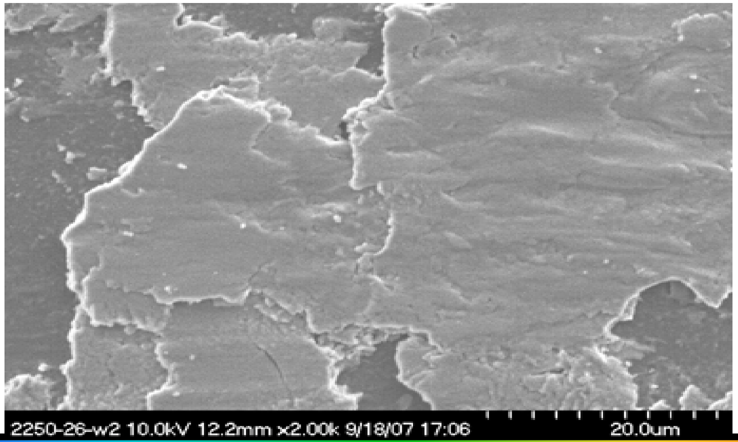
$$V = \frac{d\delta}{dt} = \frac{\frac{\beta\tau\dot{\gamma}}{\rho C} - \frac{\lambda}{\rho C}\left(\frac{\partial^2 T}{\partial X^2}_{\delta} - \frac{\partial^2 T}{\partial X^2}\right)}{\frac{\partial T}{\partial X}_{\delta}}$$

- Both scuffing initiation and propagation can now be quantitatively connected to material properties

Technical Accomplishments to Date

- Based on material properties, ceramic/contact pairs showed significant scuff resistance.
  - CSI =μLS -measures frictional energy to cause scuffing
- Scuffing in ceramic/metal pairs involves metal transfer to ceramics
- Other energy dissipation mechanisms were observed
  - Phase transformation, cracking



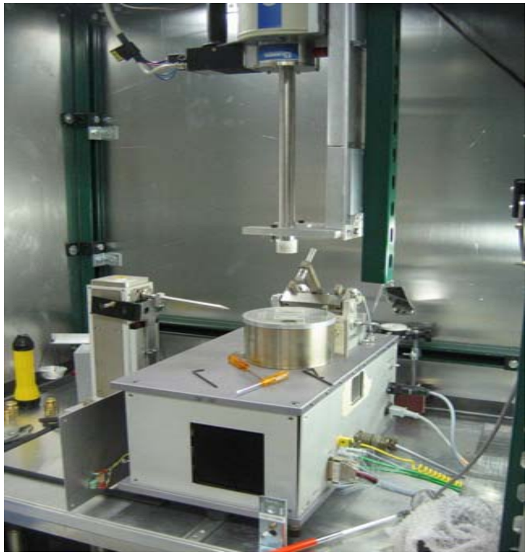


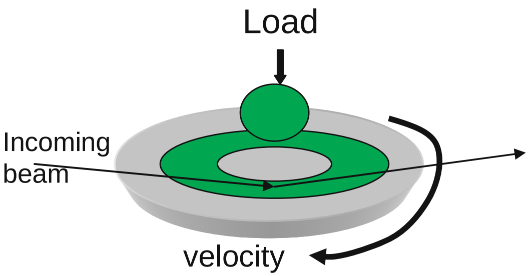
Technical Accomplishments to Date – Tribo films

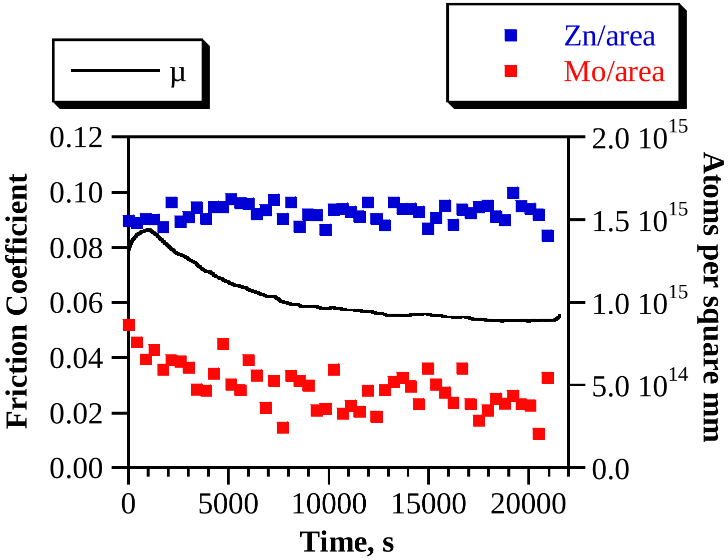
- Demonstrated usefulness of x-ray based surface analytical techniques for boundary layer characterization at APS in Argonne
  - X-ray fluorescence, x-ray diffraction, X-ray reflectivity

- Designed and constructed x-ray accessible tribometer for XRF

- Useful results, but more information needed
  - Plan to redesign rig – suitable for in-situ testing at APS

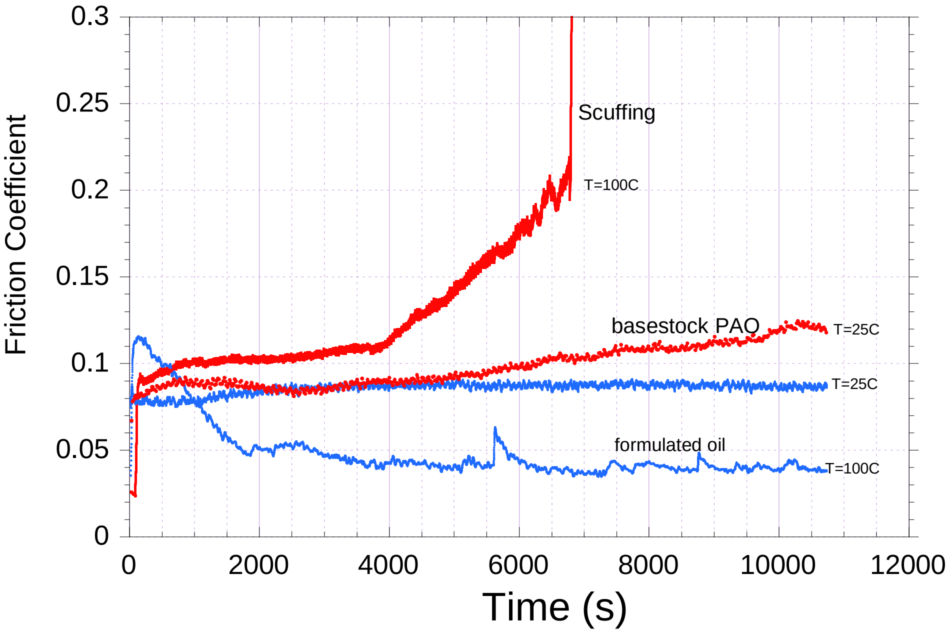


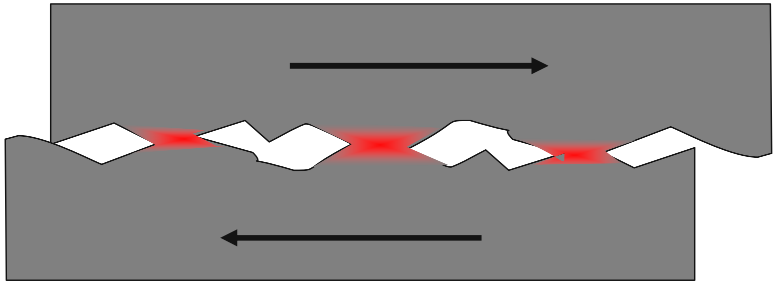




Technical Accomplishments to Date - Temperature

- Temperature has significant effect on boundary layer formation – as expected.
- Need to measure the real temperatures at the points of contact where surface reaction occurs





FY 08 Work Plan and Accomplishments to date

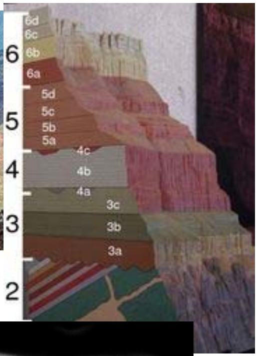
- Microscopy and profilometry of tribo-chemical films
- Continue evaluation of scuffing mechanisms for non-metallic materials
  - Continue refinement of scuffing model
- Initiate the measurement of boundary film mechanical and frictional properties
- Continue the development of real contact temperature measurement in lubricated sliding.

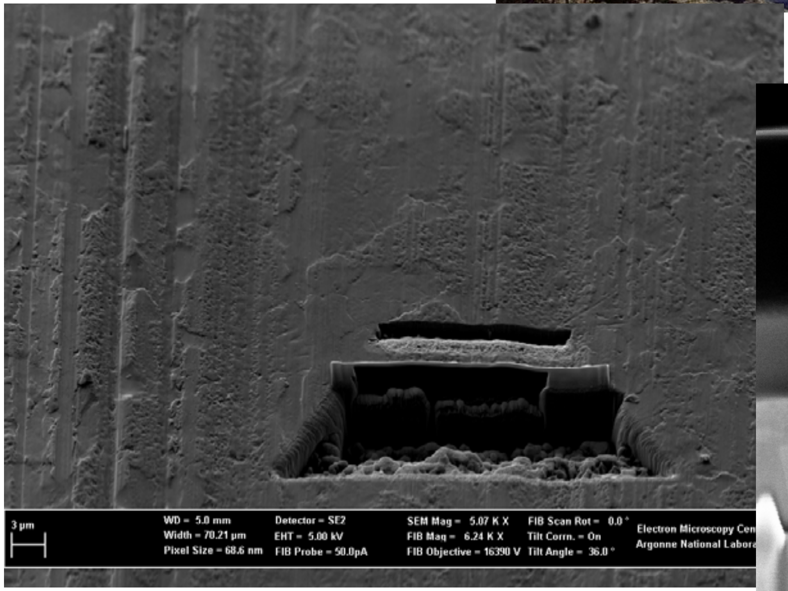
FY08 Accomplishments to date:

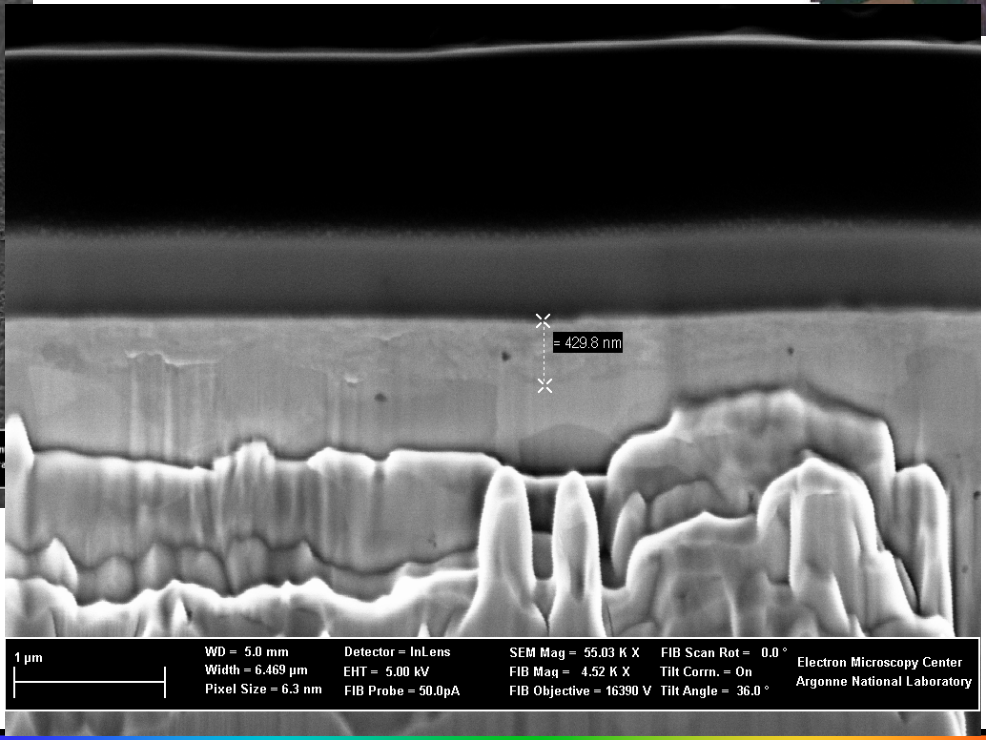
- Initiated FIB analysis of low-friction boundary films
- Progress in understanding metal/ceramics contact scuffing mechanism
- Initiated development of a technique to measure real contact temperatures.

FY 08 - accomplishment

- FIB analysis of boundary layer - Learning from nature

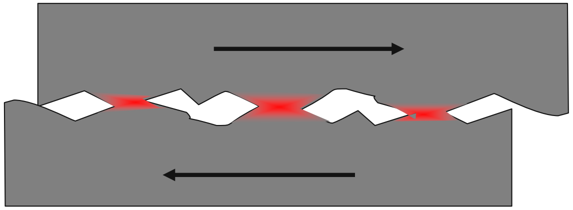


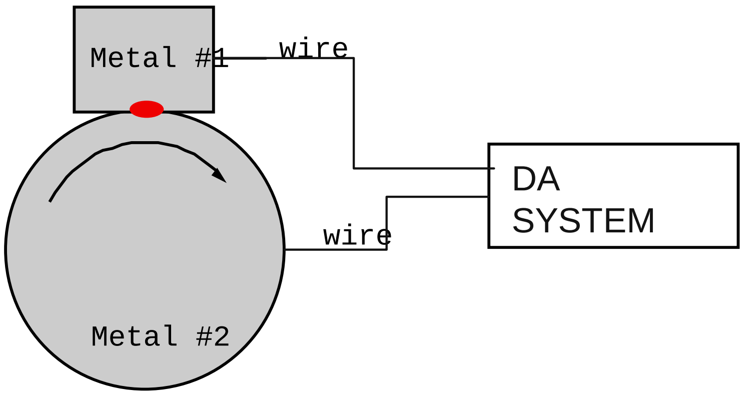


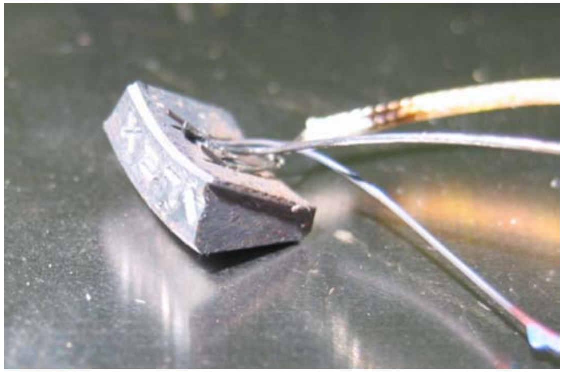


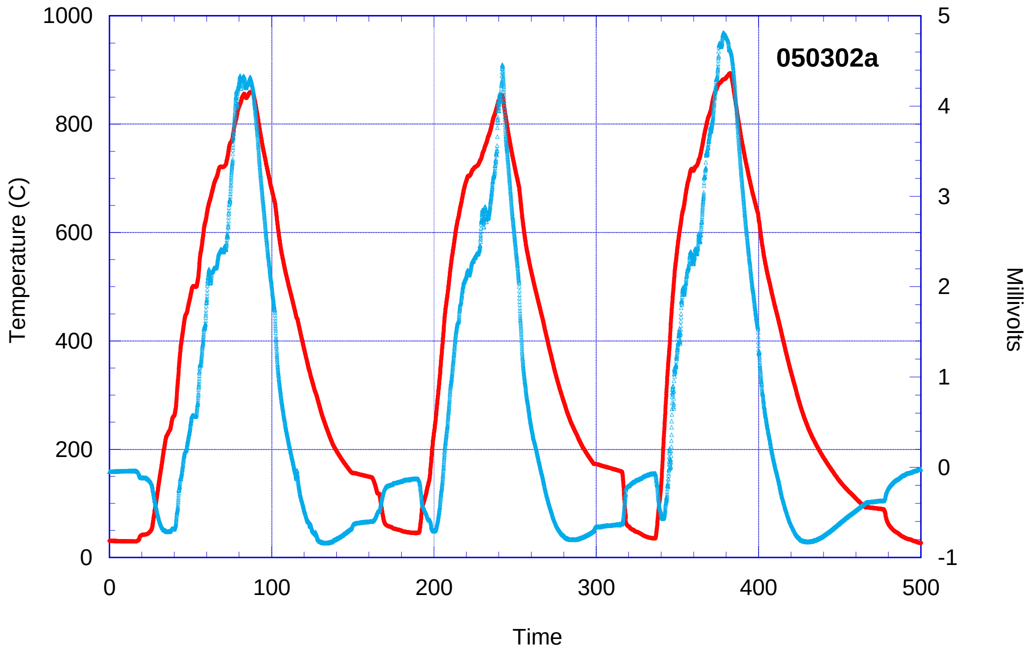
FY- 08 accomplishment

- Contact temperature measurement – thermoelectric potential approach
- Proof of concept demonstrated.









Technology Transfer

- Initiative by industrial collaborator to develop high power density driveline system.

- Initiated collaboration with the two leading lubricant additive manufacturers and a major oil company to apply some of film characterization techniques in their product development.
  - Development of low-friction lubricants
  - Need for lubricant formulation for non-ferrous surfaces
  - Need to reduce, eliminate and/or substitute some additive components

Future Plans

- Continue the study and refinement of scuffing model to include all classes of materials, especially ceramics and thin-film coatings.
- Redesign and refine the x-ray accessible tribometer for in-situ study of film formation at the APS.
- FIB and TEM analysis of low-friction boundary layer films.
- Develop contact temperature measurement technique and apply to lubricated broad spectrum of lubricated contacts.
- Measure and model the frictional properties of boundary layer, and its impact on component performance.
- Integrate models of near-surface material, boundary layer and fluid films to develop a method/model to predict friction and wear between realistic component surfaces in tribological contact.

Summary

- Increase in vehicle systems and components power density facilitated by better understanding and prediction of scuffing will result in significant petroleum displacement
  - Size and weight reduction in many systems
  - Efficient and cost effective product development

- Boundary films can be optimized for low-friction and durable contact interface with adequate information on the formation and loss rates, the structure, mechanical and frictional properties that the current project will provide
  - Effective and efficient lubricant formulation for various materials
  - Prediction of friction for real surfaces and lubricants

- Results of the project have general applicability.

- Potential for 5 -15 % fuel savings increasingly achievable

The end

Additional materials

Publications, Presentations, Patent

- 12 Peer reviewed Journal publications
- 6 Peer reviewed conference proceedings
- 15 Conference presentations
- 6 Reports
- 1 patent application, and 1 invention disclosure

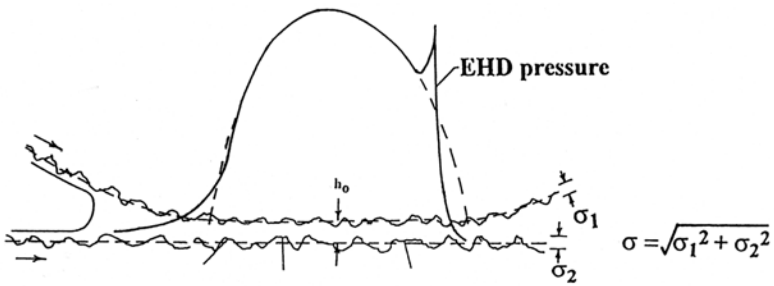
DOE Technical Barriers addressed by Project

Vehicle Technologies program mission – Develop more efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.

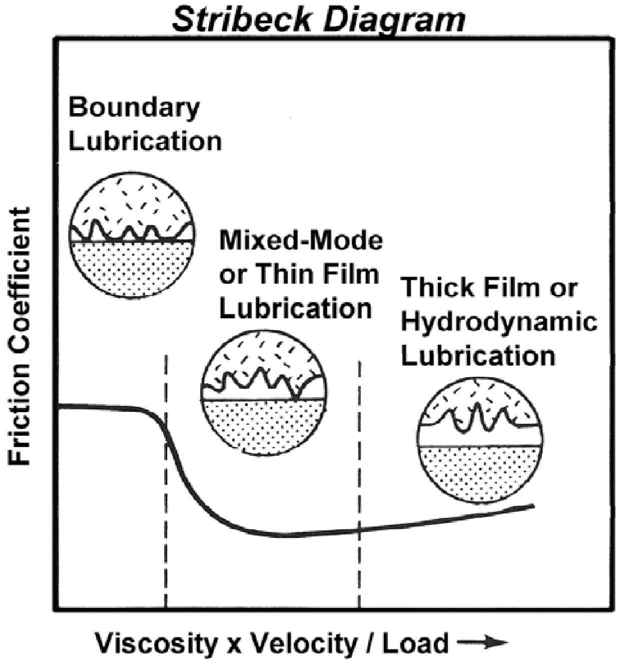
- "Develop technologies to reduce the parasitic losses from heavy vehicle systems"
- From 21 CTP technology road map: "Friction, wear, and lubrication limit engine efficiency. Higher in-cylinder temperatures necessary for higher efficiency require significant advances in tribology"
- Stated need: "Develop a better understanding of frictional effects, and develop materials and lubricants with enhanced tribological properties to address the multiple surface interactions that occur in heavy vehicle systems".

Background - Lubrication Regimes

Three main lubrication regime depending on the ratio of lubricant film thickness to the composite surface roughness – so called λ ratio



Lubricant fluid film knowledge relatively matured through elastohydrodynamics (EHD) theory and experiments



Boundary lubrication is complex:
–Poor understanding of chemical films and near-surface material behavior

Biggest payoff in terms of friction reduction is in the boundary regime.

Challenges of Boundary Lubrication

- Boundary lubrication regime involves the three structural elements simultaneously and changes continuously with time.
  - Requires system engineering approach of integration of the behavior of the three elements.
  - Current approach is Edisonian trial and error.

- Unable to characterize formation and properties of boundary films and changes in material surface in real time.

  - Post-test analysis after surface cleaning.
  - Parametric studies for wear and scuffing

- Opportunity:

  New tools and technology to facilitate in-situ analysis of boundary film formation and properties measurement, as well as dynamic changes in material surface.

  -APS at Argonne

  -Scanning probe microscopy (AFM, STM ….)

  - Nano indentation