Friction Modeling for Lubricated Engine and Drivetrain Components

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Project ID # PM026

Overview

Timeline

- Start date - Jan. 2010
- End date - FY2015
- Percent complete – 10%

Budget

- Total project funding
  - DOE share – 170K
  - Contractor share
- Funding
- FY10 – 170K

Barriers

- Barriers addressed
  - Safety, durability, and reliability
  - Computational models, design and simulation methodologies
  - Higher vehicular operational demands

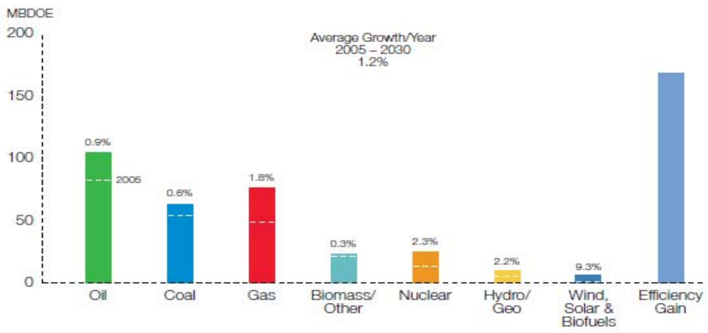
Partners

- Interactions/ collaborations
  - Castrol-BP
  - Oakland University

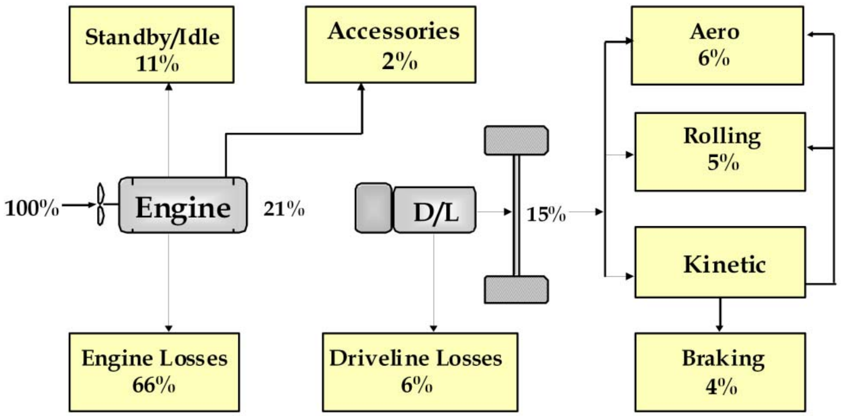
Project Description and Relevance

- Efficiency gain is the largest source of energy
- In transportation vehicles, only about 1/3 of energy from fuel is used for mobility
  - Rest lost to engine and drivetrain inefficiencies, idling, etc
  - Opportunities for significant improvement
- A major source of inefficiencies in vehicle is friction in engine and driveline components

growing global energy demand
by fuel type – 2030



Energy Distribution Typical Mid-Size Vehicle



Project Objective and Relevance

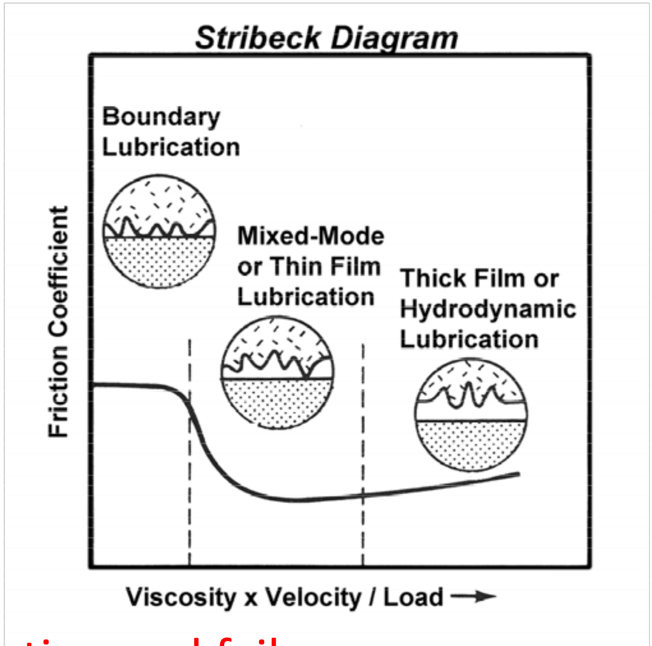
- **Technical Need:** Currently, there is no comprehensive model to predict friction at lubricated component surfaces. The existing models are based only on fluid film lubrication. Most engine and driveline components operate under mixed and boundary lubrication regime. A comprehensive model that can adequately predict friction in all lubrication regimes is needed.
  - Provide effective approach and methodology for sustainable friction reduction and the consequent efficiency gain in transportation vehicle engines and drivelines

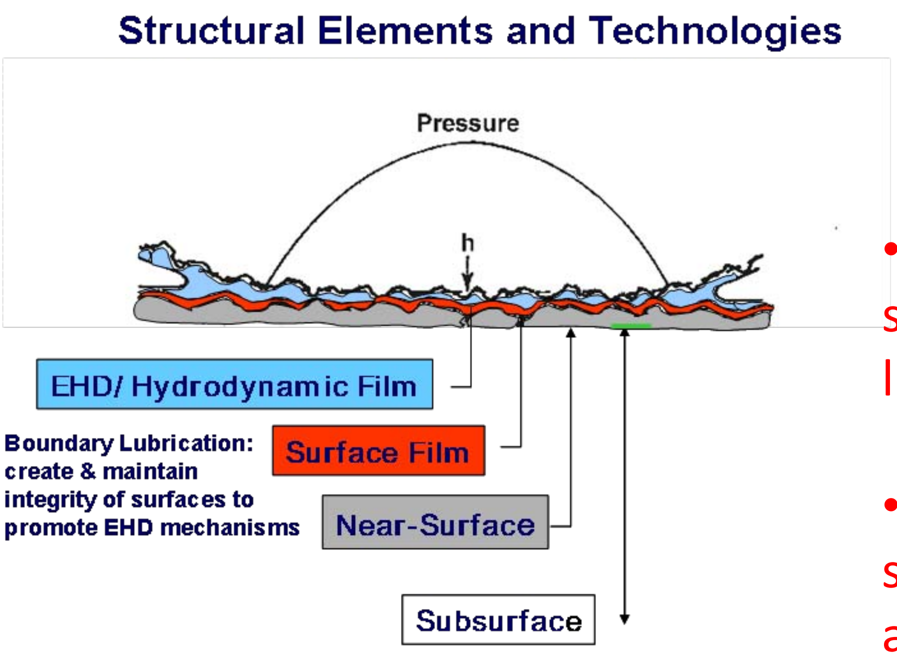
- **Project Objective:** Develop a comprehensive model and tool(s) to adequately predict the friction at sliding and rolling contact interface operating under all lubrication regimes.

Sources of Friction in Sliding (Lubricated) Contacts

Three structural elements:

- Lubricant fluid films (Hydrodynamic and EHD)
- Tribochemical surface reaction films (boundary films)
- Near-surface materials





Wedeven et. al - AFRL-VA-WP-TR-2001

- Highest friction and failure susceptibility occurs in boundary lubrication regime.
- Surface films and near-surface material structural elements dominate friction and wear behavior – these two elements are not included in existing friction models.

Technical Approach

- The approach to comprehensive modeling of friction will be based on simultaneous shearing of the three structural elements, i.e. lubricant fluid film, tribochemical boundary film, and the near surface material at a contact patch.

  Friction coefficient (μ) = ∑ (shear force for each element)/Normal Force

$$\mu = \frac{F_{sf} + F_{sb} + F_{sa}}{F_N}$$

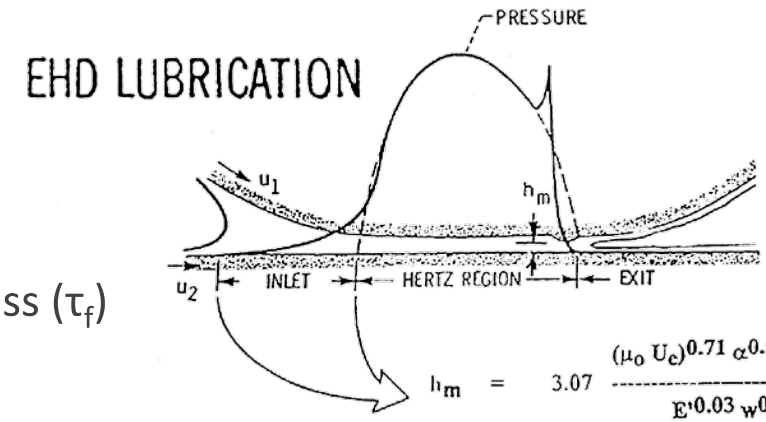
F_{sf} = Fluid film shear force
F_{sb} = Boundary film shear force
F_{sa} = asperity shear force

- The total friction can be calculate by integration the shear forces of the three elements over the entire contact area as a function of time taking into account contact parameters and surface roughness.

- Develop constitutive equation for the shear behavior of each of the three structural elements.
  - Basis for the eventual development of codes and tools to predict friction in all lubrication regimes.

FY10 Technical Accomplishments – fluid film

- Analysis and prediction of the lubricant fluid film element of lubrication is relatively matured. The fluid film thickness and the shear stress in the fluid at a loaded sliding contact can be adequately calculated.



$$h_m = 3.07 \frac{(\mu_o U_e)^{0.71} \alpha^{0.57} R^{0.40}}{E'^{0.03} w^{0.11}}$$

where

h_m	mimimum film thickness
R	combined radius of curvature $R = 1/2(R_1 + R_2)$
w	applied load
U_e	entraining velocity $U_e = 1/2(U_1 + U_2)$
μ_o	viscosity at atmospheric pressure
α	pressure-viscosity coefficient
E'	combined elastic modulus

- There are models for fluid film shear stress (τ_f)

$$\tau_f = \mu_0 e^{\alpha P} \frac{S}{h_m}$$

S = sliding velocity
P = contact pressure

Fluid film shear force (F_{sf}) can calculated by multiplying the shear stress by fluid contact area (A_f) i.e.

$$F_{sf} = \tau_f A_f$$

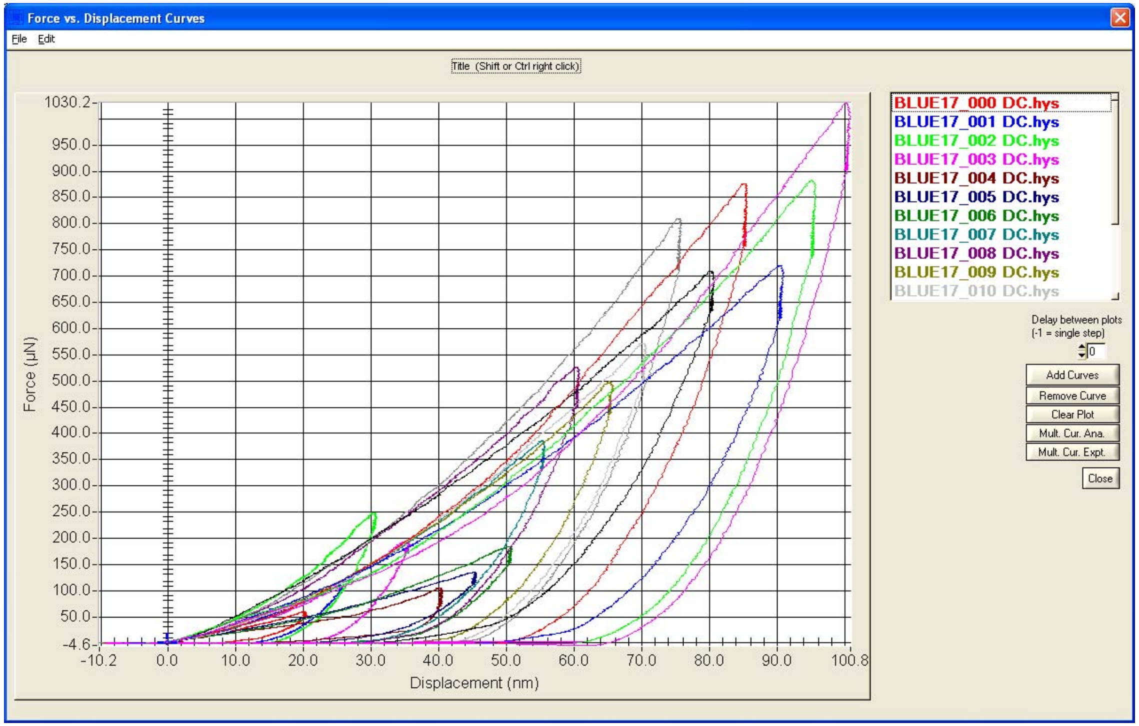
FY10 Technical Accomplishments: Boundary Films

- The mechanical behavior of the boundary film is the least understood of the three structural elements. It has to be experimentally determined by an instrumented nano-mechanical probe system

- From the loading and unloading curves of nano-indentation, the mechanical behavior of boundary films can be determined and a constitutive equation for shear formulated.

- Boundary films have been shown to be order of 100 nm thick. Instrumented nano-indentation to different depth will be used to determine mechanical properties of boundary films.

- Nano scratch will also be used to measure shear behavior directly.



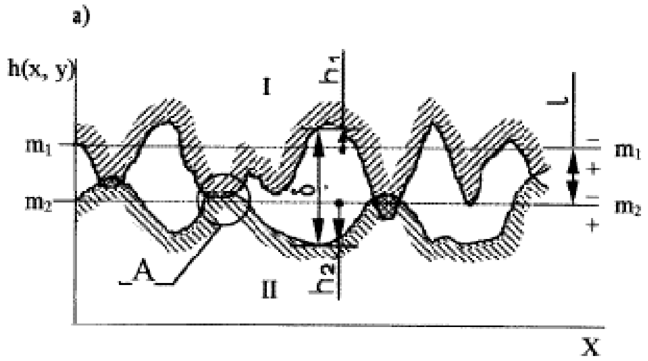
FY10:Technical Accomplishments - near surface material

- There are some useful analysis of shear behavior of surface asperities in contact

Shear stress (τ_{as}) at a single asperity in contact can be estimated:

$$\tau_{as} = P_a \tan(\phi_a)$$

Where P_a = the asperity contact pressure
φ_a = asperity high angle



For multiple asperities in contact, the overall shear stress at the interface due to asperities in contact can be estimated as:

$$\tau_{as} = \frac{1}{A}\sum_{j=1}^{j=n} a_j p_{a,j} \tan(\phi_{a,j})$$

Interfacial Frictional force due to asperity shearing:

$$F_{as} = \tau_{as} A$$

Collaborations

- **Oakland University, Rochester, MI**: Collaborate to develop model for asperity contact temperatures during sliding for both dry and lubricated contacts
  - Results of temperature calculation will be integrated into the interface shear analysis
  - Role of temperature incorporated into the new model

- **Castrol-BP:** Collaboration to formulate lubricant additives to form boundary films with different shear properties and behavior
  - Will enable adequate modeling of the contribution of the surface boundary films to friction of lubricated components.

Proposed Future Work

- Measure nano mechanical properties of boundary films in both indentation and scratching modes
  - Films with different macro-frictional behaviors and compositions will be evaluated.
  - Formulate constitutive equation(s) for shear behavior of boundary films.

- Integrate the shear equation(s) for boundary films with the shear behavior of lubricant fluid film and near surface material asperities to formulate a comprehensive friction predictive model
  - Take into account the effect of surface roughness/texture

- Using the Argonne Leadership Computing facility (ALCF), develop codes and tools to prediction friction at lubricated sliding interface.

Summary

- Friction reduction in various lubricated components transportation vehicle engines and drivelines is reliable means of increasing efficiency

- Unfortunately, friction at a lubricated interface (especially under boundary regime) is a complex phenomenon involving the shearing of the lubricant fluid film, the tribochemical boundary films and the near-surface material
  - Consequently friction prediction in boundary regime is difficult
  - Most components operate in boundary regime.

- With recent advances in instrumentation and computing technologies, it is now possible to develop a comprehensive model and tools to adequately prediction friction under all lubrication regimes (including boundary)

- This project is embarking on such mission. Constitutive equation for the structural elements of lubrication are being worked out and advanced computing facility at Argonne will be use for developing appropriate codes and tools.