Argonne NATIONAL LABORATORY

DOE/DOD Parasitic Energy Loss Collaboration

George Fenske, Robert Erck, and Nicholaos Demas

Argonne National Laboratory

May 16th, 2012

Project ID # VSS005

vss005_fenske_2012_o

U.S. DEPARTMENT OF ENERGY

Overview

Timeline

Project start date	FY 10
Project end date	FY 15
Percent complete	35%

Budget

Total Project Funding	$700K
– DOE Share	$700K
– Contractor Share*	$550K
FY 11	$125K
FY 12	$250K

- TARDEC funding in FY09
- CRADA share - $150K/FY12

Barriers

- Engine and Vehicle Efficiency
  - Reduce Consumption of Imported Petroleum
- Reliability & Durability
  - Extreme Tribological Environments (DOD/TARDEC)
  - Low-SAPS Lubricants (DOE)
  - EGR-Tolerant Lubricants (DOE)
  - Alternative-Fuel Lubricants (DOE)

Partners

- TARDEC
- Mahle
- DOD Vehicle OEMs (NDA protected)
- Ricardo Inc. (CRADA)
- Additive and Lubricant OEMs (NDA)

Overview - Role of Parasitic Friction Losses in Vehicle Economy

- This project examines the effect that parasitic friction losses have on vehicle fuel economy, durability, and reliability:
  - Examines trade-offs among lubricants, additives, materials, and engineered surfaces with regard to fuel economy and other vehicle performance requirements (emissions, durability, wear).
  - Includes impact of driving cycles on engine friction to predict friction mean effective pressure (FMEP) at different engine modes (load and speed).
  - Identifies technical goals (asperity friction, viscosity, surface finish, wear-resistance) for advanced concepts.
- Project involves major activities on simulation, lab-scale tribology, and engine validation:
  - Integration of advanced engineering-based simulation codes to predict FMEP for critical engine subsystems/components.
  - Lab-scale evaluation of tribological concepts to provide critical input data (asperity friction) for simulation codes and to identify candidate technologies that can provide target friction properties.
  - Validation of codes and experimental data using fired engine.
- Goal is to develop a common strategy to address efficiency for both DOE and DOD applications.
- Project is co-supported by VTP Fuels and Lubricants Program.

Fuel efficiency is a common concern for civilian and military sectors. Advanced low-friction technologies can reduce fuel consumption and enable use of non-petroleum alternative fuels.

Commercial Vehicles

Well-established fuel-supply/delivery system supplies **12-14 MBBL/day** at $3-4/gal.

Friction consumes 10-15% of fuel – large incentive to reduce petroleum consumption with fuel-efficient lubricants.

Military Vehicles

Incentive to improve efficiency due to high visibility of fuel supply convoys coupled with operation in remote terrains.

Delivery of fuel is complex and expensive, and can be deadly.

Reducing demand for fuel will decrease exposure of troops to hostile environment.

Reliability/Durability goals are often different, but have common fundamental failure mechanisms.

Commercial Vehicles

Emission control concepts are sensitive to lubricant additives, EGR recirculates combustion products back to oil.

Alternative fuels – lubricant formulation and fuel dilution.

Downsizing aggravates component stresses, requiring more robust lubricants.

Military Vehicles

Severe/extreme operational environments – SWA to artic, abrasive environments.

Loss-of-lubrication incidents – survivability of systems even for short periods.

Multifunctional lubricants – common engine and transmission lubricants.

Relevant DOE/VTP Goals & Missions (Multi-Year Program Plan 2011-2015, Dec. 2010)

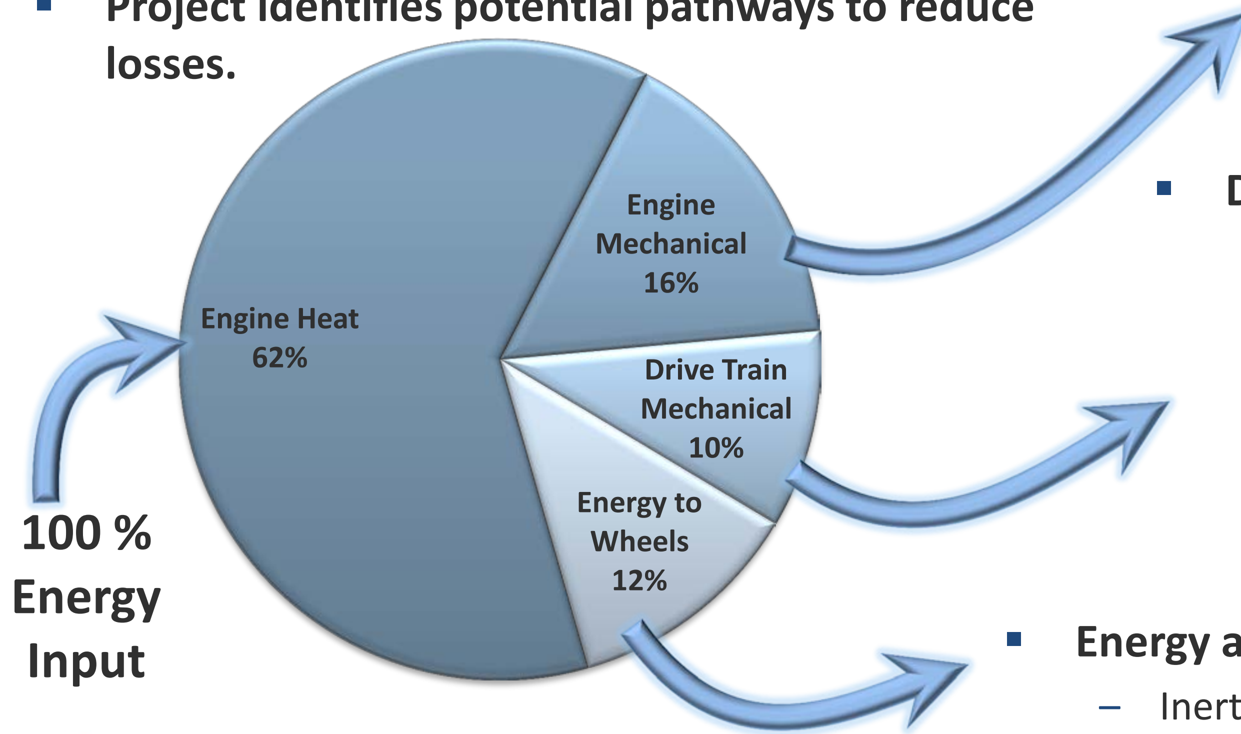
- **Light-Duty Vehicles**
  - By 2015, develop technologies and a set of options to enable up to 50% reduction in petroleum-based consumption for light-duty vehicles.
  - By 2030, develop technologies and deployment strategies, enabling up to 80% of the energy for light-duty vehicles to be from non-carbon or carbon-neutral energy sources.
- **Heavy-Duty Vehicles**
  - By 2015, demonstrate a 50% improvement in freight hauling efficiency (ton-miles per gallon).
- **21st-Century Truck**
  - Develop and demonstrate an emissions-compliant engine system for Class 7-8 highway trucks that improves the fuel efficiency by 20% (from approximately 42% thermal efficiency today to 50%).
  - Develop new diesel fuel formulation specifications, which include the use of renewables and other nonpetroleum-based blending agents, that enable achieving high-efficiency and low-emission goals while displacing petroleum fuels by 5% .
- **Advanced Vehicle Power Technology Alliance** - Department of Energy**/** Department of Army Technical Workshop and Operations Report (Oct. 2011)
  - Alternative fuels and lubricants - increase fuel economy 1-3 % (engine), 2% (driveline).

Milestones

- **FY 2011 (completed)**
  - Identify tribological issues and barriers common to military and commercial/automotive vehicles. Preliminary analysis on impact of lubricant viscosity and boundary friction on fuel economy
    - Identified parasitic engine friction models; initiated CRADA/licensing agreements.
    - Identified approach to perform ΔFMEP calculations to model impact on fuel economy.
  - Initiate/extend studies on impact of additives and materials on vehicle efficiency (**friction**) and **reliability/durability** (wear and scuffing) – in progress.
    - **Friction** – Maximum FMEP arises from viscous/hydrodynamic – focus on low loads (≈to 1 N/mm).
    - **Durability/Reliability** – Maximum forces occur near top dead-center, where boundary/mixed regimes dominate – focus on high loads (≈50 N/mm).
- **FY 2012 (in progress)**
  - Establish statement of work and initiate licensing agreements on commercial software packages to model parasitic friction losses.
  - Establish experimental protocols to develop database on high-fidelity boundary friction data for parasitic friction loss calculations.

Relevance/Objectives: More energy is lost to friction than is delivered to the wheels - approximately 10% in engine and 5% in the drivetrain (1.1-1.7 MBBL/day)

- **Project applies advanced engine friction models to predict where parasitic friction losses occur and how advanced tribological concepts can reduce losses – component by component.**
- **Project identifies potential pathways to reduce losses.**



- **Engine Mechanical Losses**
  - Pumping work
  - Overcoming friction
    - Rings and piston skirt
    - Valve train
    - Bearings & seals
  - Accessories
- **Drive Train Mechanical Losses**
  - Overcoming friction
    - Transmission
    - Differential
    - Bearings & seals
  - Coasting and idle work
  - Braking work
- **Energy at Wheels**
  - Inertia, rolling resistance, air resistance, gravity (grades)

Project Approach: Parasitic friction modeling, experimental data, and engine validation

Install Codes…Define Input…Define Tribo-Parameter Space… Run Codes…Analyze Data…Establish Look-Up Tables

Phase 1
MODELING
Predictive "Look-Up Table" Database

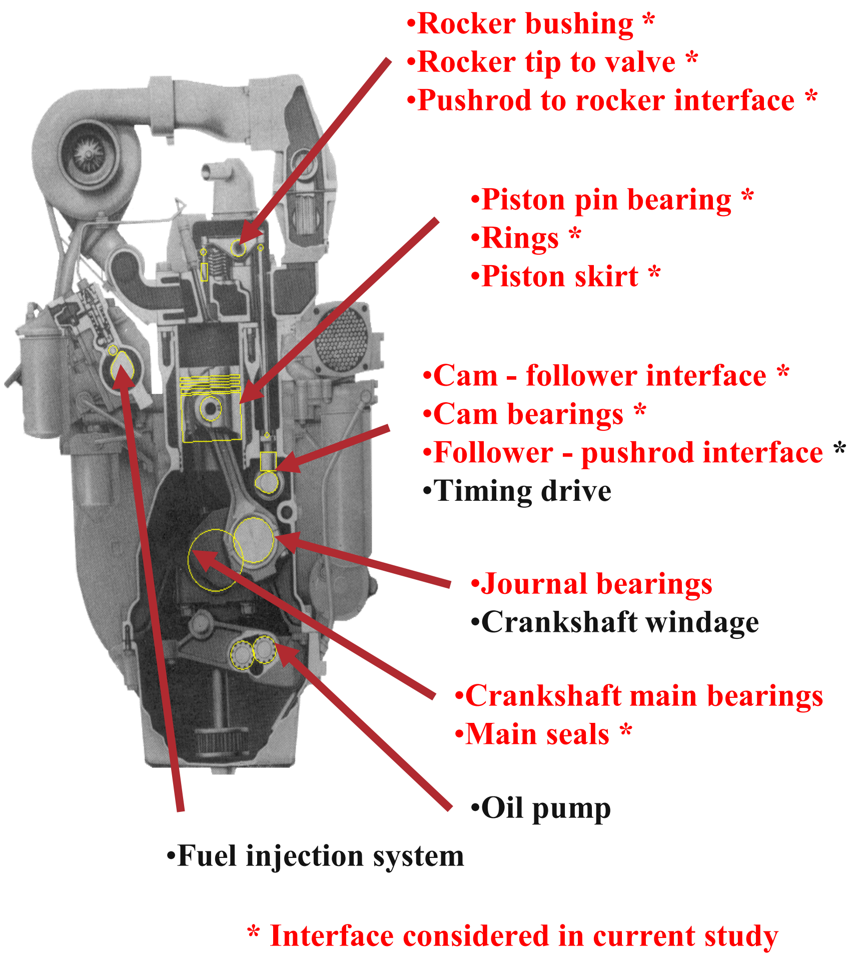
Establish Simulation Conditions…Perform Simulation Studies…Analyze Data…Develop BF Database

Phase 2
EXPERIMENTAL
Boundary Friction Database:
Temperature, Composition, Lubricant, Finish

Identify Engine Technique …Contract… Validate…Analyze

Phase 3
VALIDATION
Code/Data Engine Validation

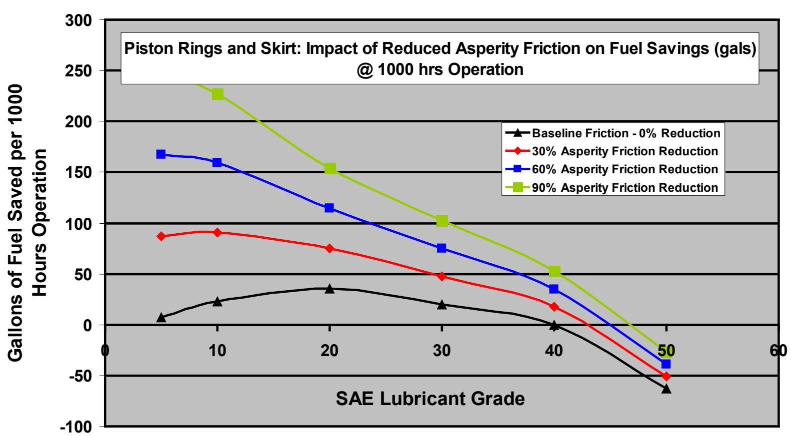
Progress (Phase 1 - Modeling): Based on previous studies, identified specific codes to model losses

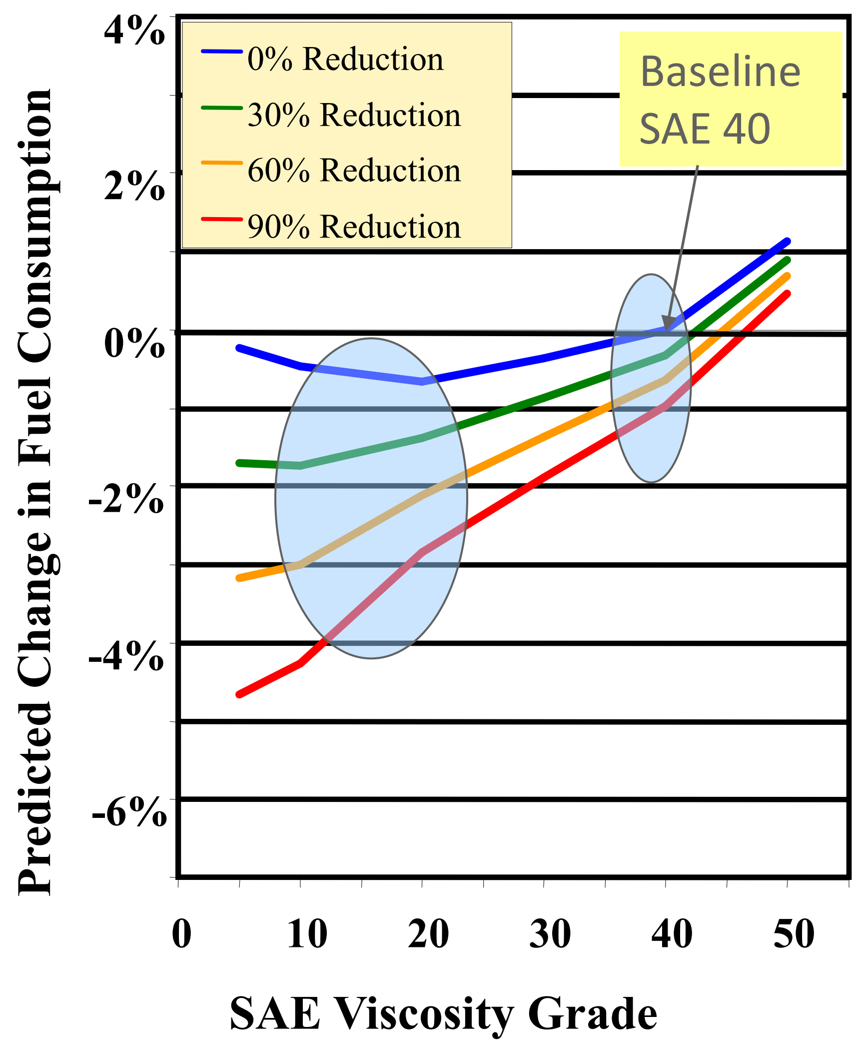


- Results from 4 software codes will be integrated to model FMEP as functions of tribological parameters and engine mode.
- PISDYN
  - 3D simulation of piston dynamics and secondary motion. Friction losses, scuffing, and wear loads.
- RINGPAK
  - 2D simulation of ring pack dynamics, lubrication, and gas flow. Friction losses, wear loads, and oil consumption.
- VALDYN
  - Multi-body simulation of valve train and drive component friction forces/losses.
- ENGDYN
  - 3D analysis of crank train, engine structure, and associated components (bearings, connecting rods, mounts). Friction losses – bearing contact.

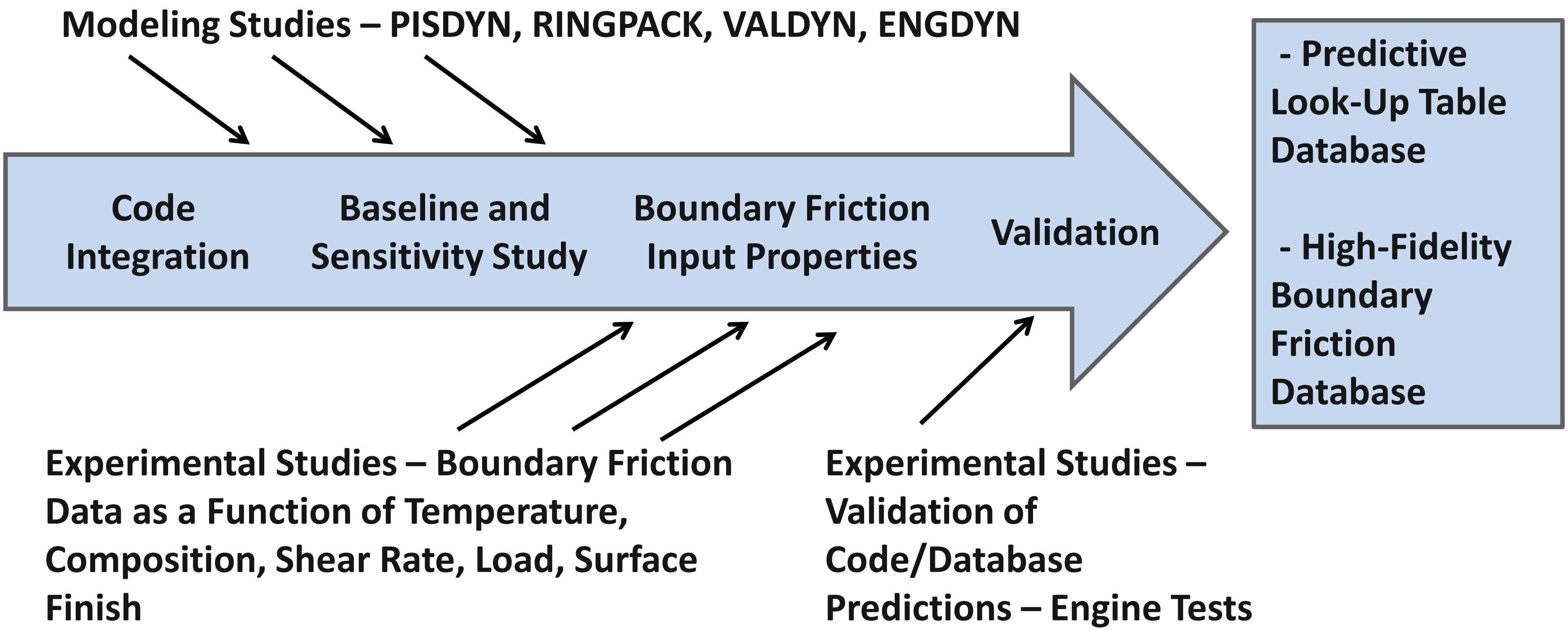
Previous Results Limited to HDD only: Impact of engine size, engineered-textured surfaces, synthetics NOT considered - Modeling effort expanded to include these parameters

- **Prediction/Modeling of Fuel Savings**
  - Systematic studies on the effect of boundary friction and oil viscosity on fuel efficiency
  - Up to 1.3% fuel economy improvement by low friction additives and/or coatings
  - 3-4% fuel economy improvement by reducing boundary friction and oil viscosity
  - Additional 2-4% fuel economy gains in transmission and differential/axle



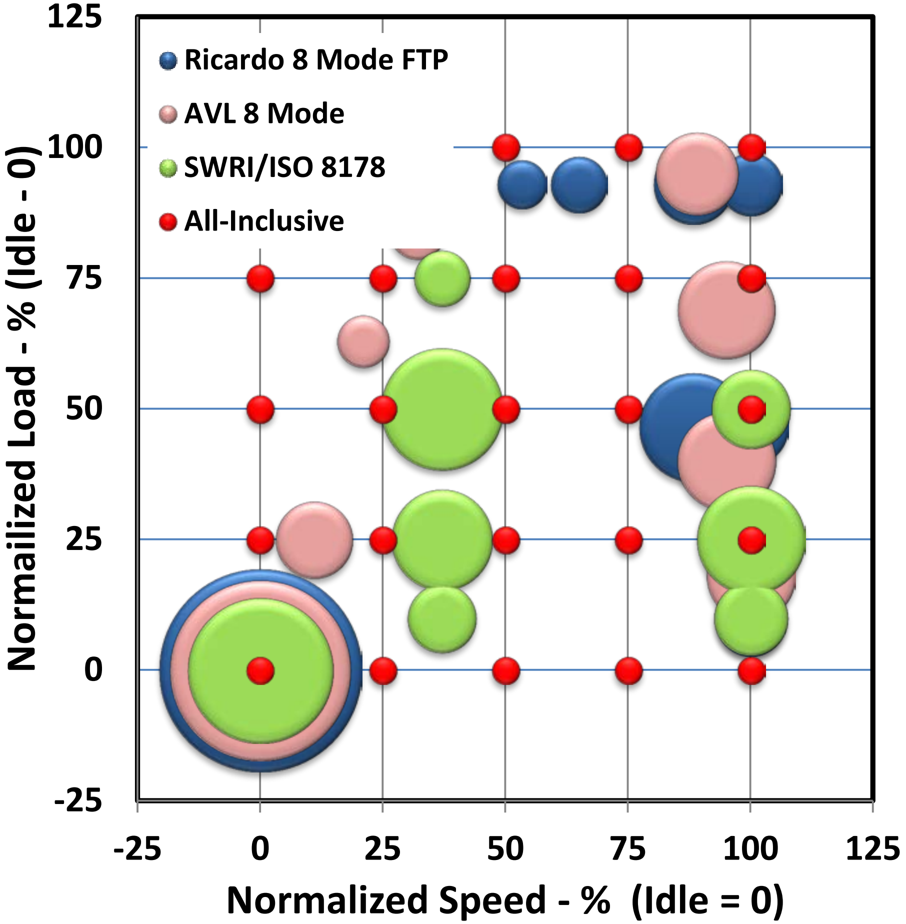


Progress (Phase 1 - Modeling): Statement of Work (SOW) and detailed tasks developed and incorporated into CRADA package; CRADA approved by DOE and partner; CRADA in final negotiation



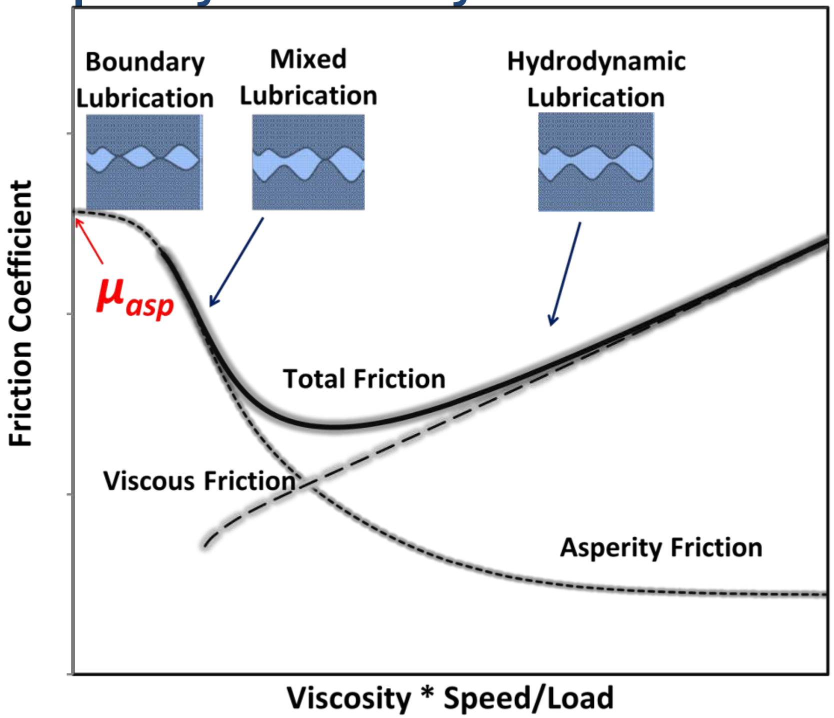
Progress (Phase 1 - Modeling): Realistic drive cycles (load-speed and weighting factors) are required to predict FMEP and impact on fuel economy; commercial cycles “well” established; military cycles are NOT “well” defined

- Rather than waiting for well-defined drive cycles, the modeling effort will proceed using an all-inclusive range of modes (5 x 5 or 4x4), eliminating unreasonable modes (low speed /highest loads).
- Individual user of database will select specific modes and weighting factors subject to sum of weighting factors adding up to 100%.
- For the purpose of establishing the look-up tables, using a more inclusive range of engine modes will mitigate the need for narrow, drive-cycle specific engine modes.
- Currently preparing for installation of codes on ANL cluster machine.



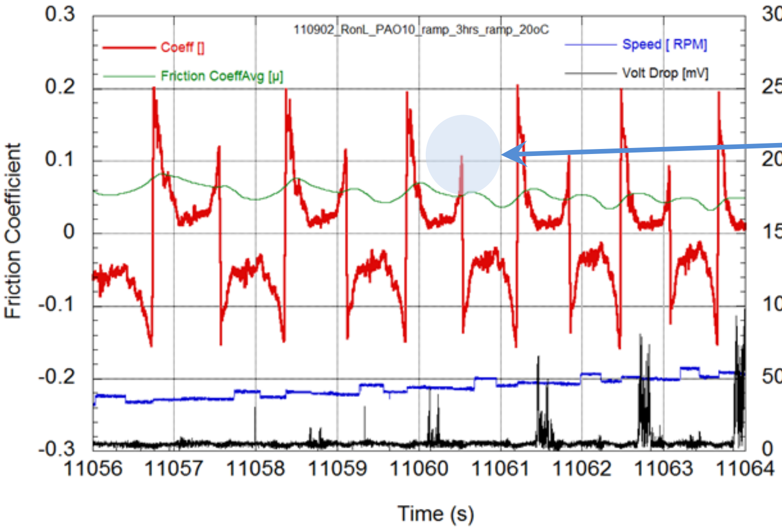
Progress (Phase 2 - Experimental): Identified lab-scale configurations and protocols to extract high-fidelity asperity/boundary friction data

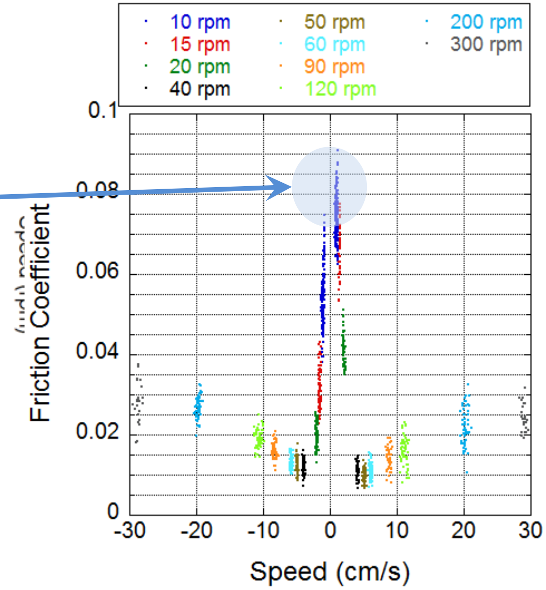
- FMEP simulation codes require input on asperity friction to model boundary and viscous friction losses.
- Typically, the asperity friction is treated as a fixed constant, depending on the component (e.g., μ_{asp} = 0.08 for skirt, 0.12 for rings).
- Asperity friction is not a fixed constant – it is affected by temperature, shear rate, and additives.
- Phase 2 – Experimental activities focus on developing realistic data on asperity friction to improve the fidelity of the FMEP simulations.
- **Lab-scale test configurations and test protocols are being developed to provide asperity friction data .**

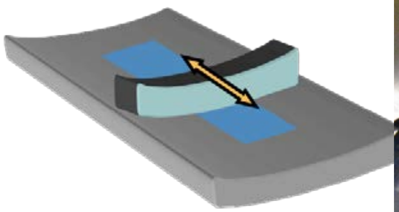


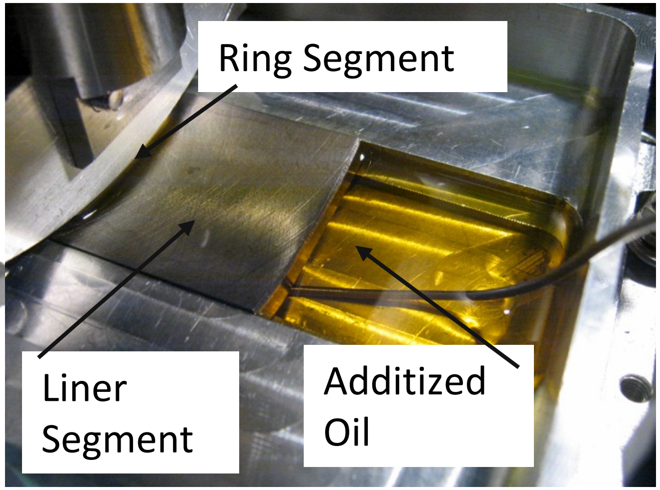
- Lab-scale tests will be performed to develop realistic asperity (boundary) friction data for accurate FMEP predictions.
- μ_{asp} (as shown in the Stribeck curve) will be determined experimentally for “zero” Stribeck values.

Progress (Phase 2 - Experimental): Developed protocols for high-fidelity database on asperity/boundary friction μ_{asp} using bench-top rigs



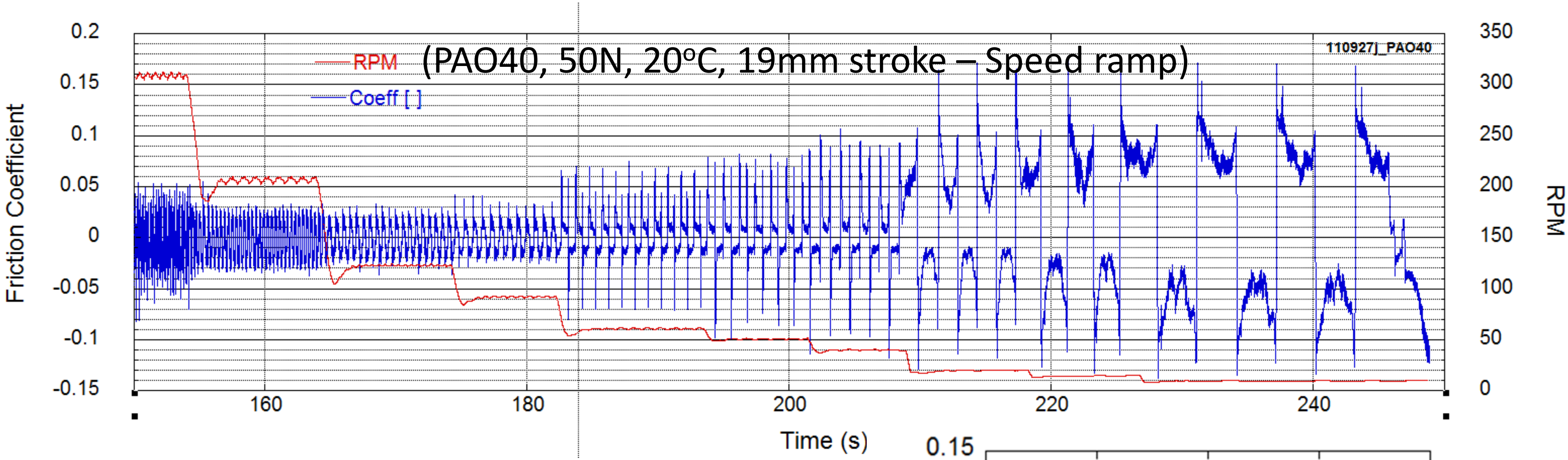




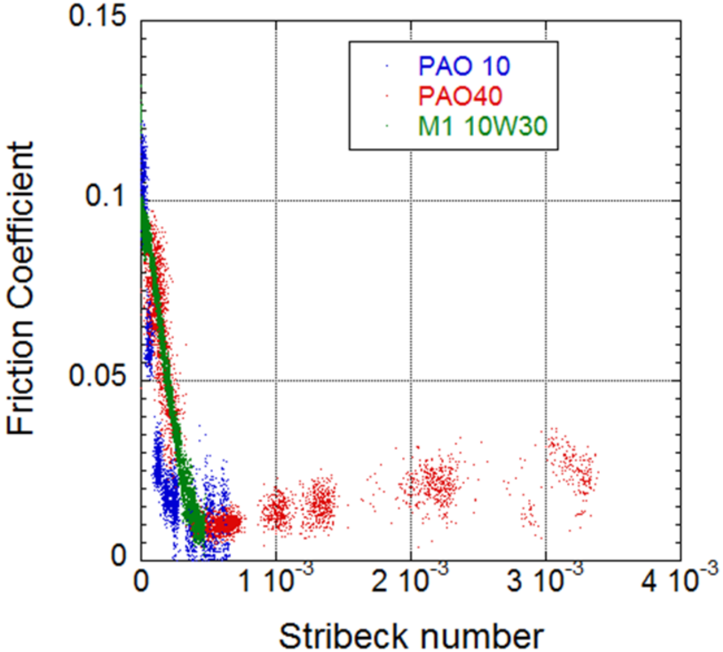


- Utilize reciprocating rig to measure friction (boundary, mixed, and hydrodynamic) on actual component surfaces.
- Provide data on boundary friction coefficient for codes:
  - Temperature effects
  - Tribo-film composition/make-up

Progress (Phase 2 - Experimental): Developed approach to extract μ_{asp} data from bench-top tests using Stribeck parameter

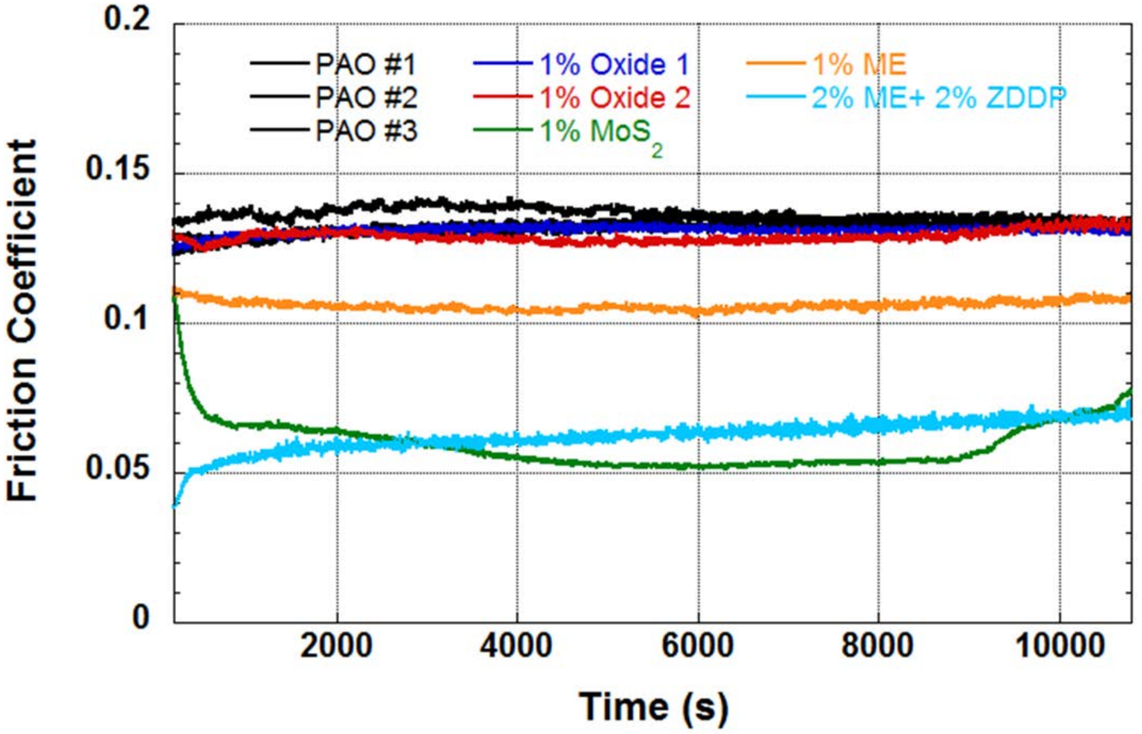


- Experimental friction data obtained from bench-top rigs can be analyzed as a function of the Stribeck number (η* V/L) for different lubricants to extrapolate back to a zero Stribeck number.
- Different additives (antiwear and friction modifiers) and temperatures should exhibit distinct values of μ_{asp} .



Progress (Phase 2 – Experimental): Initiated evaluation of advanced additives to evaluate their impact on friction

- Ring-on-liner tests were initiated to examine the role of several advanced additives on friction.
- Tests were performed in unformulated lubricants to avoid interaction with other constituents.
- Several candidates were observed to **reduce friction up to 60%** (MoS_2 powder and a Mo-based ester). Synergistic effect observed with anti-wear additive.
- Tests with formulated lubricants in progress.



- This work is **co-supported by Fuels and Lubricants (F&L) Program**. The information obtained from these studies will be incorporated into friction database for FMEP modeling project.
- Strong leverage of F&L to provide information for finite element interface modeling.

Collaborations and Coordination

- Ricardo – CRADA partner; FMEP simulation software, modeling consultation.
- DOD/TARDEC - Force Projection Technologies/Fuels and Lubricants Technology Team – Provide guidance on DOD requirements, contacts with suppliers, and collaboration on lubricant characterization and testing.
  - Development of engine and drivetrain lubricants
- Engine Component OEM (Mahle) - Provide prototypic engine components.
  - Rings, pistons, & liners
  - Modeling of friction and wear during bench-top tests
- Lubricant supplier(s) [industry] – Provide baseline and experimental oil formulations.
  - Mil-spec oil – engine & drivetrain
  - Commercial lubricants – nanoadditives
- Project direction and objectives are coordinated with other DOE/VT programs.
  - Vehicle systems (drivetrain), and
  - Fuels & lubricants (additives, tribological testing, and characterization)
- Collaborative efforts with MIT Lubrication Consortium.

Proposed Future Activities

- Remainder FY 2012
  - Complete CRADA negotiations – final signatures.
  - Install simulation software on Argonne computing cluster.
  - Initiate calculations of FMEP for baseline engines.
  - Initiate population of asperity friction database for baseline fluids (base fluids and formulated lubricants) as a function of temperature and surface finish.

- FY 2013
  - Continue modeling of FMEP using PISDAYN, RINGPACK, VALDYDN, and ENGDYN.
  - Further define simulation design space , including engine size, engine modes, viscosity, asperity friction, surface finish, and base fluid properties (synthetic vs. mineral).
  - Asperity friction data – evaluate asperity friction properties for advanced formulations.
  - Evaluate and select protocols for engine validation phase (Phase 3); initiate subcontract.

Summary

- Established collaborative effort among Argonne, industry, and DOD to model the impact of advanced tribological concepts on fuel economy and reliability/durability.
- Developed framework for a formal CRADA with Ricardo to model FMEP using their proprietary simulation software packages – final negotiations are in progress.
- Developed experimental protocols to measure asperity under prototypical conditions and approach to analyze data to provide high-fidelity data for input into simulation codes.
- Leveraging collaborations with industry, consortia (MIT), lubricant and additive OEMs, and DOE VTP F&L programs significantly enhances the research support.