DOE/DOD Parasitic Energy Loss Collaboration

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Project ID # VSS005

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Overview

Timeline

- Project start date FY 10
- Project end date FY 15
- Percent complete 65%

Budget

- Total Project Funding $1887K
  - DOE Share $1187K
  - Contractor Share* $700K
- FY 13 $202K
- FY 14 $285K

- CRADA share - $150K/FY13

Barriers

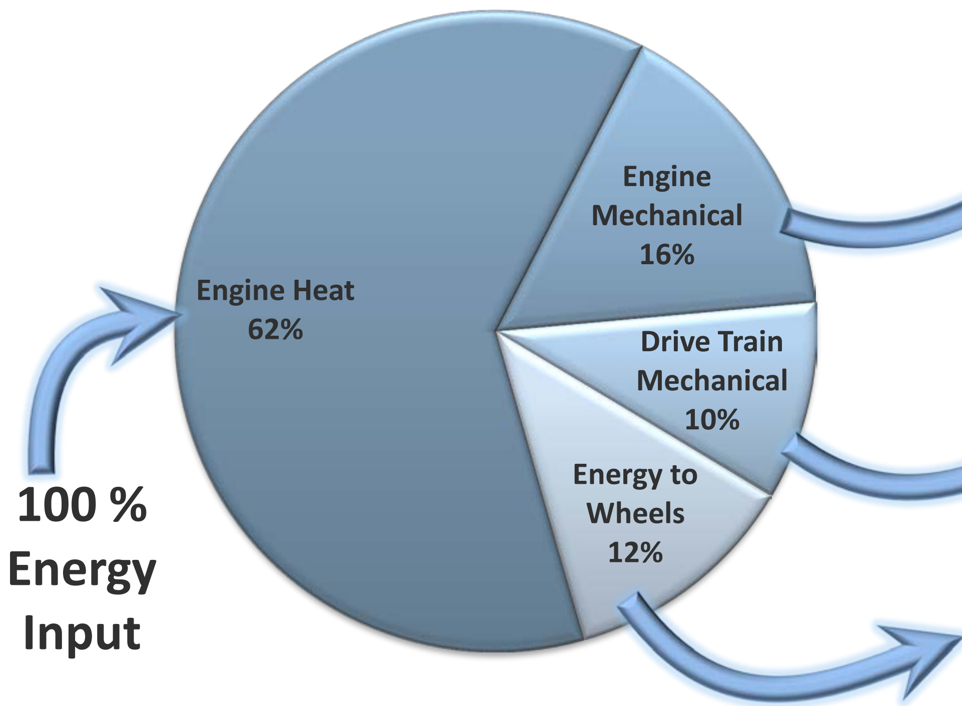
- Engine and Vehicle Efficiency
  - Reduce Consumption of Imported Petroleum
- Reliability & Durability
  - Extreme Tribological Environments (DOD/TARDEC)
  - Low-SAPS Lubricants (DOE)
  - EGR-Tolerant Lubricants (DOE)
  - Alternative-Fuel Lubricants (DOE)

Partners

- Ricardo Inc. (CRADA)
- Mahle
- TARDEC
- US Truck OEM (NDA)
- Additive and Lubricant OEMs (NDA)

Relevance/objectives: A surprisingly large fraction of the fuel used for transportation is lost to friction - approximately 10% in engine and 5% in the drivetrain (1.1-1.7 MBBL/day). Advanced, low-viscosity, friction-modified lubricants have the potential to reduce friction losses for NEW and LEGACY vehicles.

- **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, and gravity (grades)

Relevance to DOE and DOD: Although civilian and military applications and drive cycles differ significantly, both sectors will realize significant benefits with improved tribological concepts (although for different reasons). The challenge is to improve both fuel economy AND reliability/durability.

Reducing friction in civilian vehicles will provide a path to achieve more stringent mileage standards (e.g., 35/55 mpg) and reduce the frequency/number of fuel supply missions for military missions.

Commercial Vehicles	Military Vehicles
Well-established fuel-supply/delivery system that 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.	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. 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	Military Vehicles
Emission control concepts are sensitive to lubricant additives; exhaust gas recirculation returns combustion products back to oil. Alternative fuels diluted in lubricants will behave differently than petroleum based fuels. Downsizing aggravates component stresses, requiring more robust lubricants.	Severe/extreme operational environments – Southwest Asia to artic, abrasive environments. Loss-of-lubrication incidents – survivability of systems even for short periods. Multifunctional lubricants – common engine and transmission lubricants.

Relevant DOE/VTO Goals & Missions - Develop a methodology to assess impact that advanced tribological systems (lubricants, materials, additives, engineered surfaces) will have on friction, and determine how they can be integrated into vehicles to achieve VTO goals on reducing petroleum consumption and emission of GHG.

- **Lubricants**
  - Develop better base oils and oil additives that may have the potential to improve the mechanical efficiency of internal combustion engines by 10 percent
- **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 parasitic friction reduction technologies that decrease driveline losses by 50%, thereby improving Class 8 fuel efficiencies by 3% (Roadmap and Technical Papers – 21st Century Partnership, Feb 2013).
- **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).

Project Goal: Develop (1) FMEP database using physics-based models to quickly estimate effect of viscosity and friction on fuel economy and (2) database on experimental asperity friction coefficients as functions of temperature, additive composition, friction modifier, materials, and contact stresses for use with the physics-based models.

- 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, and 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, and 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.
- Goals are to:
  - Develop a public database to quickly estimate impact of viscosity, asperity friction, and surface finish on friction losses at different engine speeds and loads – FMEP map.
  - Develop an experimental database on the impact of lubricant additives, advanced materials, temperature, and contact stress on asperity friction.

Milestones: Long-term (project) milestones and near-term milestones for the Parasitic Energy Loss Project include:

- **Long-Term Project Goals**
  - Develop a web-based toolkit/calculator for rapid assessment of the impact of key tribological engine parameters on vehicle fuel economy.
  - Develop high-fidelity database on boundary friction for use in toolkit for high potential low-friction solutions.
  - Validate toolkit/calculator and database using fired-engine dyno tests.

- **Near-Term Milestones (FY13/14)**
  - Install Ricardo engine dynamic simulation codes (PISDYN, RINGPAK, ENGDYN, VALDYN) at Argonne – Completed in FY13 – CRADA.
  - Model power-cylinder FMEP for a small spark ignition (SI) engine (500 CC/cylinder). Completed in FY13.
  - Complete engine model (e.g., design input for engine components) for medium-duty diesel engine for use in Ricardo codes. Completed in Dec. 2013.
  - Complete parametric study of lubricant properties of FMEP and fuel economy for a medium-duty diesel vehicle. On-schedule as of June 2014.

Project Approach: The project entails 3 main tasks: simulate parasitic friction using physics-based codes of dynamic forces acting on engine components to develop 'look-up' tables, measure asperity friction coefficients for use in the codes, and validate the trends predicted by look-up tables.

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

Task 1
MODELING
Predictive "Look-Up Table" Database

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

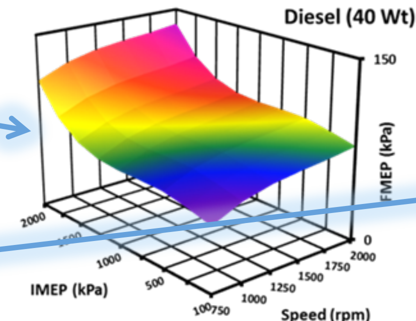
Task 2
EXPERIMENTAL
Boundary Friction Database:
Temperature, Composition, Lubricant, Finish

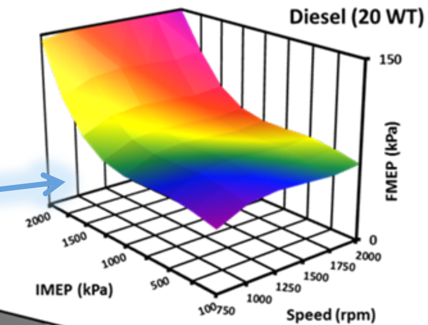
Identify Engine Technique … Validate…Analyze

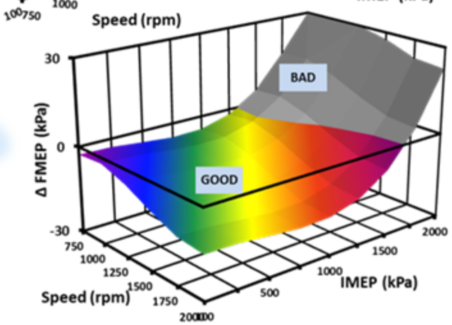
Task 3
VALIDATION
Code/Data
Engine Validation

Task 1 Approach: PISDYN and RINGPAK* are used to simulate friction force and power for different engine conditions (load, speed, viscosity, asperity friction). The output is a map of FMEP as a function of load (IMEP) and speed from which FMEP difference maps are generated to scale fuel consumption.

- Calculate/simulate FMEP map for baseline condition (e.g. 40 WT oil) as function of Load (IMEP) and speed (rpm).
- Calculate/simulate FMEP map for advanced concept (e.g. 20 WT oil).
- Calculate ΔFMEP difference map.



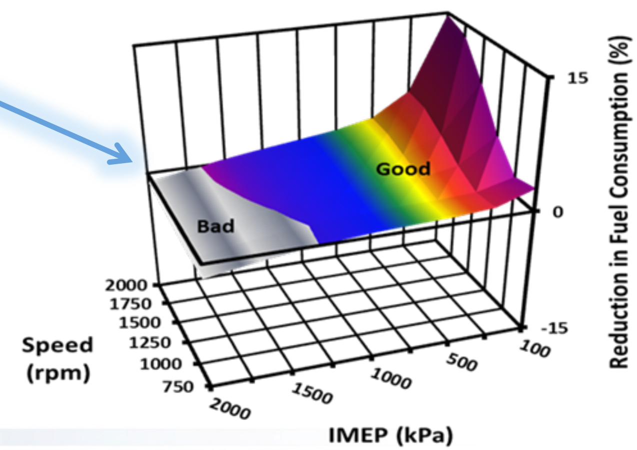




Delta FMEP - 20WT (40 WT Baseline)

- Calculate fuel consumption scaling factors and fuel economy maps.

$$FCSF(Speed, Load) = (IMEP + \Delta FMEP)/IMEP$$



- Apply drive-cycle weighting factors.

* PISDYN and RINGPAK are commercial codes provided through a CRADA with Ricardo, Inc.

Progress (Task 1 - Simulation): During FY12/13, a CRADA was established with Ricardo to access their codes for use in this project. The codes were installed, training supplied, and simulation efforts initiated.

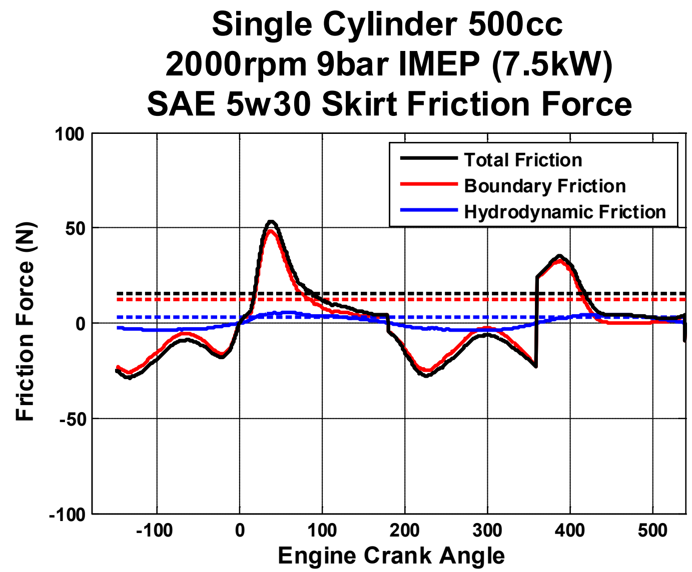
- Results from 4 software codes will be integrated to model FMEP as functions of tribological parameters and engine mode.
- PISDYN
  - 3D simulation of piston dynamics and secondary motion. Friction losses, scuffing, and wear loads.
- RINGPAK
  - 2D simulation of ring pack dynamics, lubrication, and 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, and mounts). Friction losses – bearing contact.

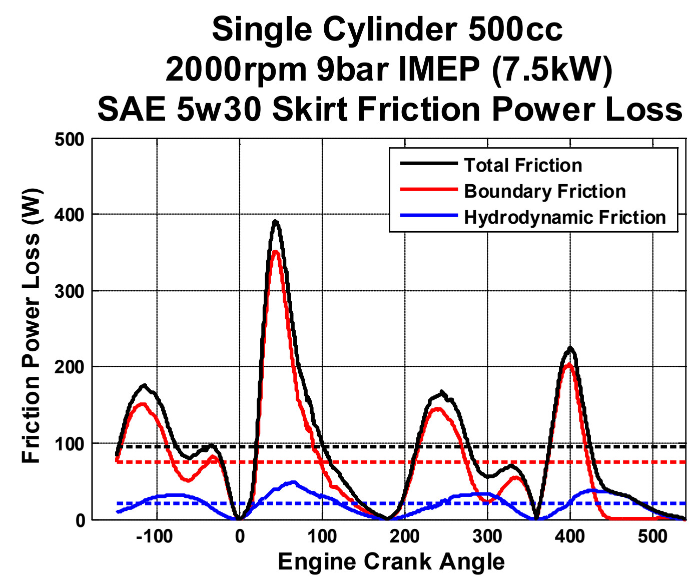
Progress: CRADA established with Ricardo, Inc., to install and use their codes, PISDYN, RINGPAK, ENGDYN, and VALDYN to simulate/model FMEP at specific engine loads and speeds for a range of engine viscosities, asperity friction, and surface finish conditions.

Codes are installed at Argonne and are operational.

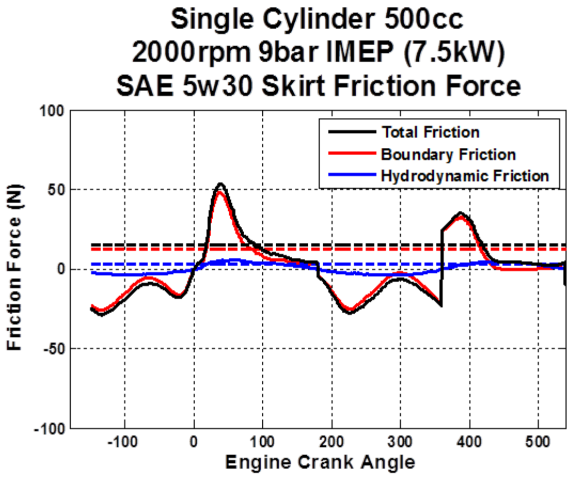
<u>Progress</u> (Task 1: Simulation) - During FY13, piston and ring friction was modeled for a small-bore SI engine. Friction force and power were modeled for different viscosities, asperity friction coefficients, and engine load/speed conditions. Instantaneous force and power losses are shown below.

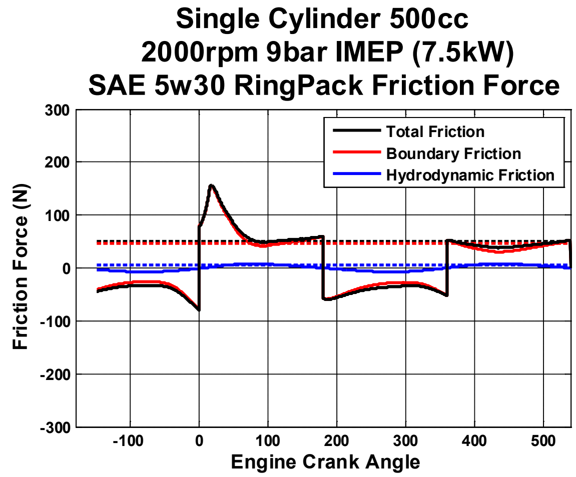
- Model for Ricardo Hydra engine implemented on ANL system.
- PISDYN AND RINGPAK codes used to simulate FMEP for a range of lubricant parameters
  - 5 viscosities (light, medium, and heavy)
  - 3 asperity friction coefficients (0.06, 0.09, and 0.12)
  - (4 speeds x 4 loads)
- Example at right illustrate the contributions from asperity/boundary friction and hydrodynamic shear. Partial lubrication (10 micron oil film on skirt/liner).

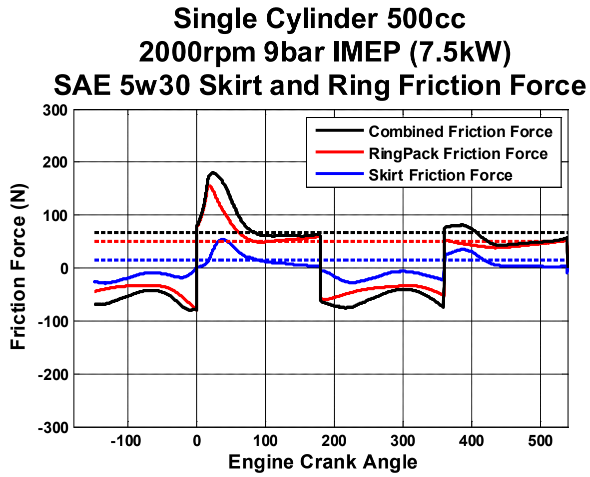




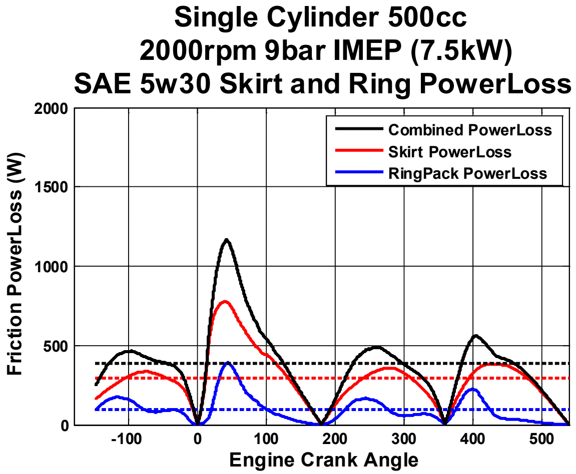
Combining skirt/wrist-pin friction with ring friction provides information on power cylinder friction losses (10-micron partial lubrication to both skirt and rings).







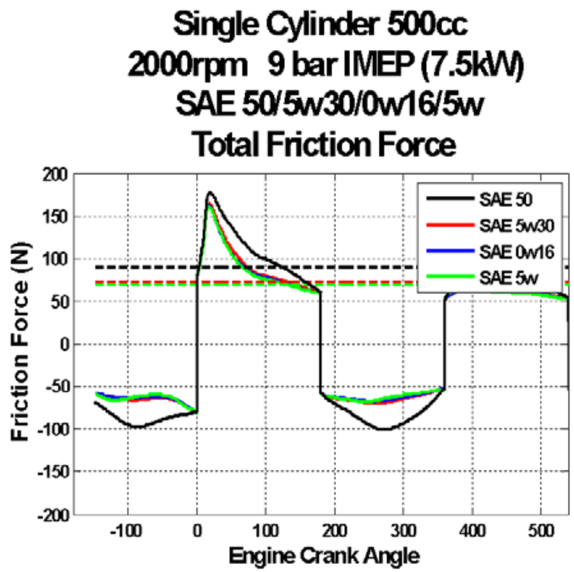
- PISDYN models friction forces and power arising from skirt/liner interactions and wrist-pin friction.
- RINGPAK models friction forces and power from ring/liner interactions.
- Examples illustrate the relative contribution of ring and piston forces on total power cylinder friction.
    - @ 9 bar/2K rpm, 5 % of IMEP is consumed by parasitic friction – 75% from the rings, 25% from the piston/wrist-pin.

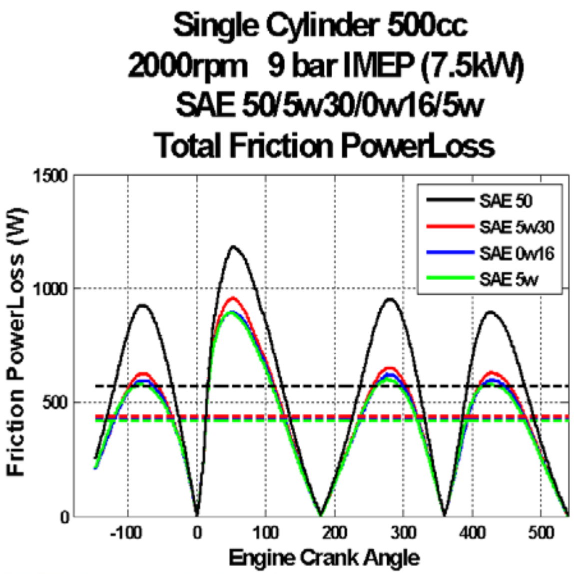


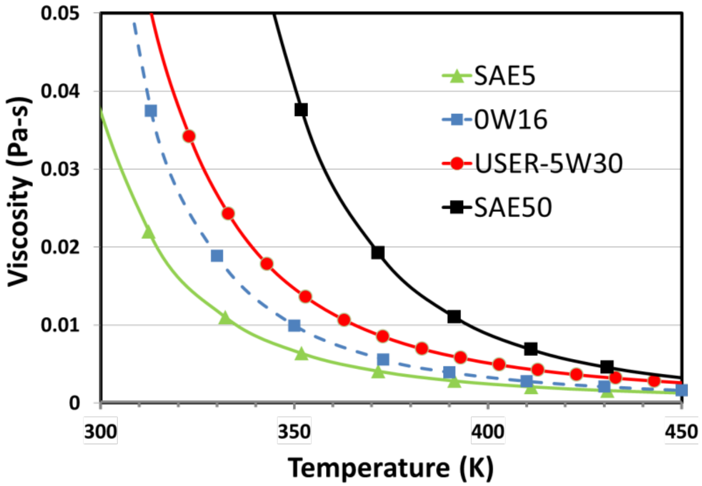
Dashed lines in the plots represent crank-angle-average friction force or power.

Task 1 Progress: Modeled/simulated the impact of viscosity on power-cylinder losses. Models illustrate higher friction power losses with heavier lubricants.

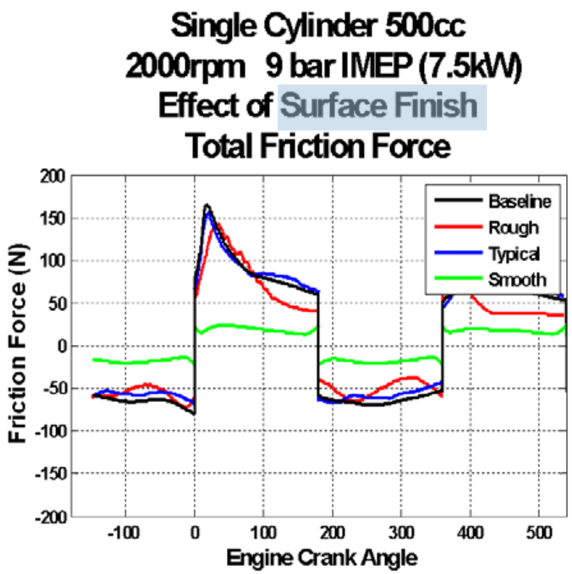
- Parametric scans on the impact of lubricant viscosity on friction losses were performed at different engine modes.
  - The figure below shows the dramatic differences in viscosity for the different lubricants modeled (light, medium, and heavy oils).
  - Figures to the right illustrate the impact of viscosity on friction losses – at this condition, the parasitic losses are greatest for the heavier oils.

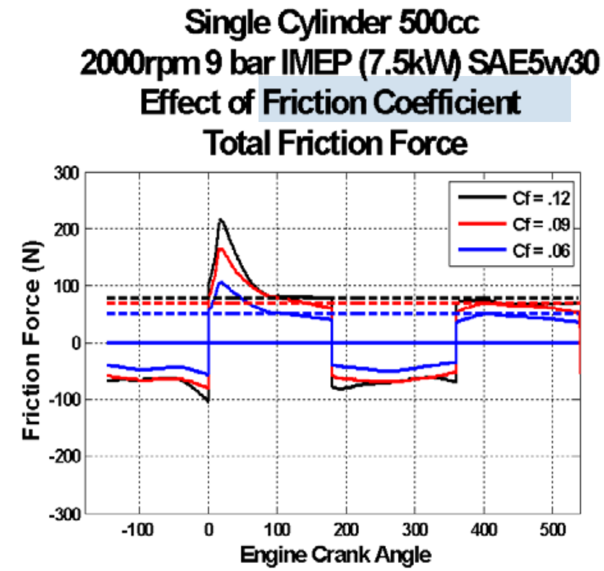




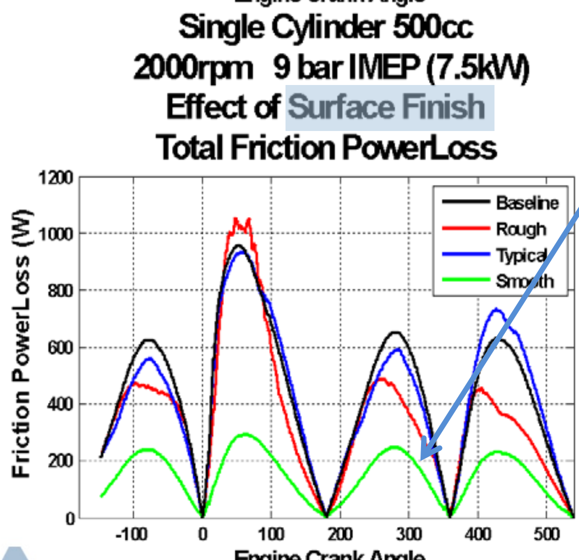


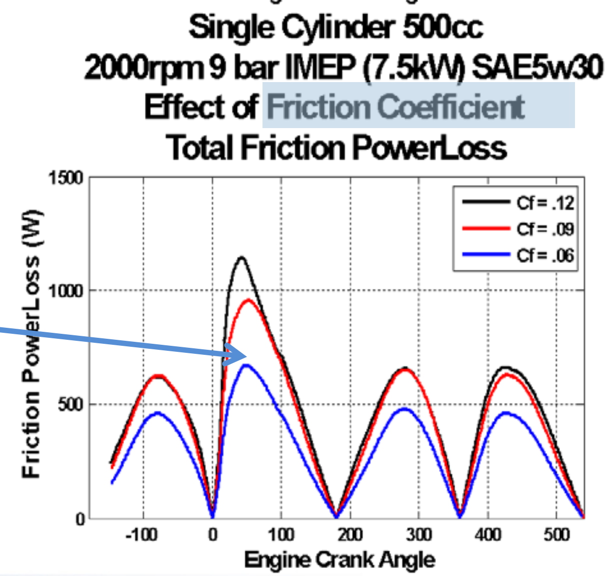
Task 1 Progress: – Application of codes to simulate the impact of surface finish and friction on power-cylinder friction forces and power losses. Significant reductions in parasitic losses with smooth liners and friction modifiers.





Significant reduction in friction losses with smoother surface finishes





Significant reduction in friction losses with low-friction surfaces

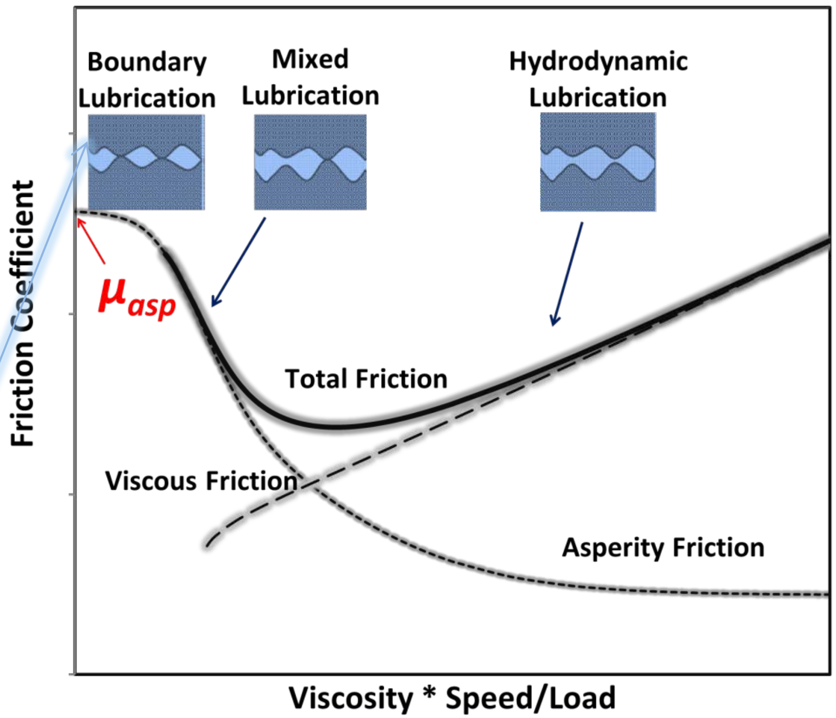
Task 1 Summary: PISDYN and RINGPAK installed, model of small SI engine implemented, and parametric scans of critical lubrication parameters performed.

- The goal of Task 1 is to implement RINGPAK and PISDYN to model parasitic friction losses in power cylinder components as functions of engine load and speed for different lubrication environments.
- The data obtained from the load x speed scans will form the basis to generate FMEP maps for different lubrication conditions, from which FMEP difference maps relative to a reference case can be used to estimate changes in fuel consumption.
- During the past year, a suite of codes (PISDYN, RINGPAK, ENGDYN, and VALDYN) was made operational at Argonne (under a CRADA with Ricardo), and studies were initiated for a small SI engine.
- The trends observed related to viscosity, asperity friction, and surface finish are consistent with automotive trends. Based on previous HDDE simulations, FMEP and fuel consumption scaling factors (FCSF) maps were developed.
- Task 1 activities for the remainder of FY14 and FY15 will focus on filling in the matrix of the tribological conditions to develop the FMEP maps and implementing a medium-duty diesel engine model.

Subtask 2 Asperity Friction: One of the critical input parameters for modeling FMEP is the asperity friction coefficient. This task utilizes high-precision lab-scale tribometers to quantify asperity friction under a wide range of conditions.

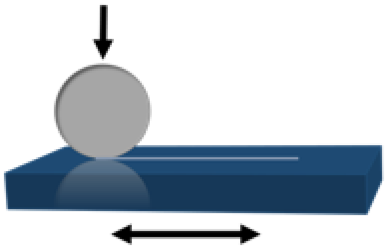
- FMEP simulation codes require input on asperity friction to model boundary and viscous friction losses.
- Typically the asperity friction is treated as a fixed constant, depending on the component (e.g., μ_{asp} = 0.08 for skirt, 0.12 for rings).
- Asperity friction is not a fixed constant – it is affected by temperature, shear rate, and additive chemistry.
- **Lab-scale test configurations and test protocols have been developed to provide asperity friction data.**

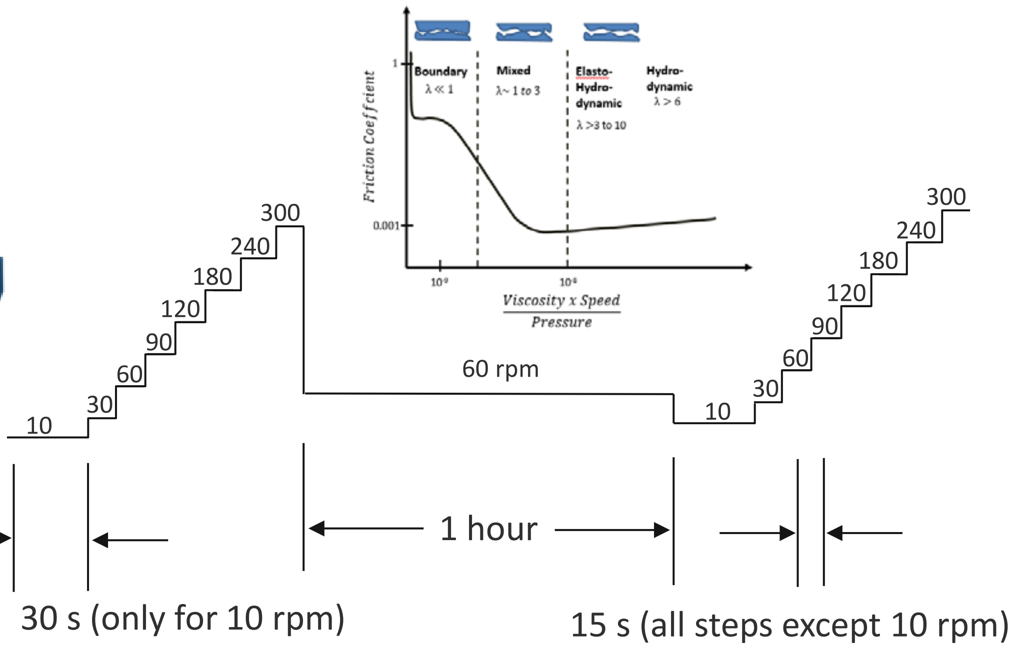
μ_{asp} is required for the codes

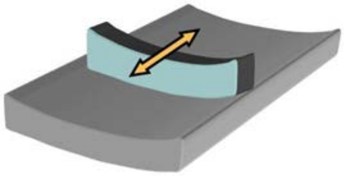


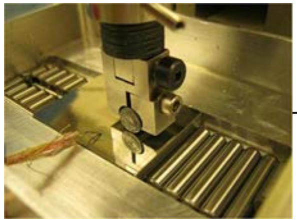
- Lab-scale tests are being performed to develop realistic asperity (boundary) friction data for accurate FMEP prediction.
- μ_{asp} (as shown in the Stribeck curve) will be determined experimentally for “zero” Stribeck values.

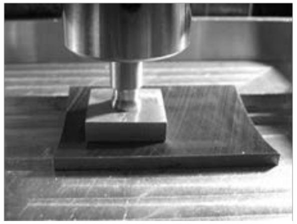
Argonne developed test protocols to measure friction using simple ball-on-flat configurations and ring-on-liner configurations that are ideally suited to measure friction under boundary and mixed lubrication conditions using prototypic segments of rings and liners.











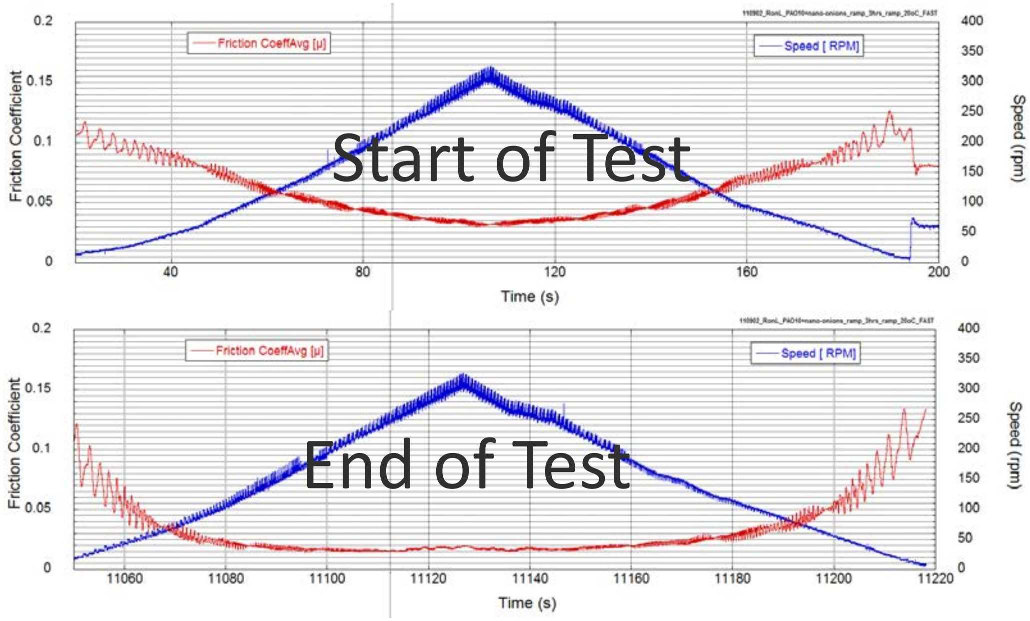
- Initial Hertzian contact pressure of 1 GPa
- Speed: up to 0.2 m/s
- Temperature: up to 160 ^{o}C

- Initial Hertzian contact pressure of ~ 5 MPa
- Speed: up to 0.2 m/s
- Temperature: up to 160 ^{o}C

Differences between real engine and reciprocating rig

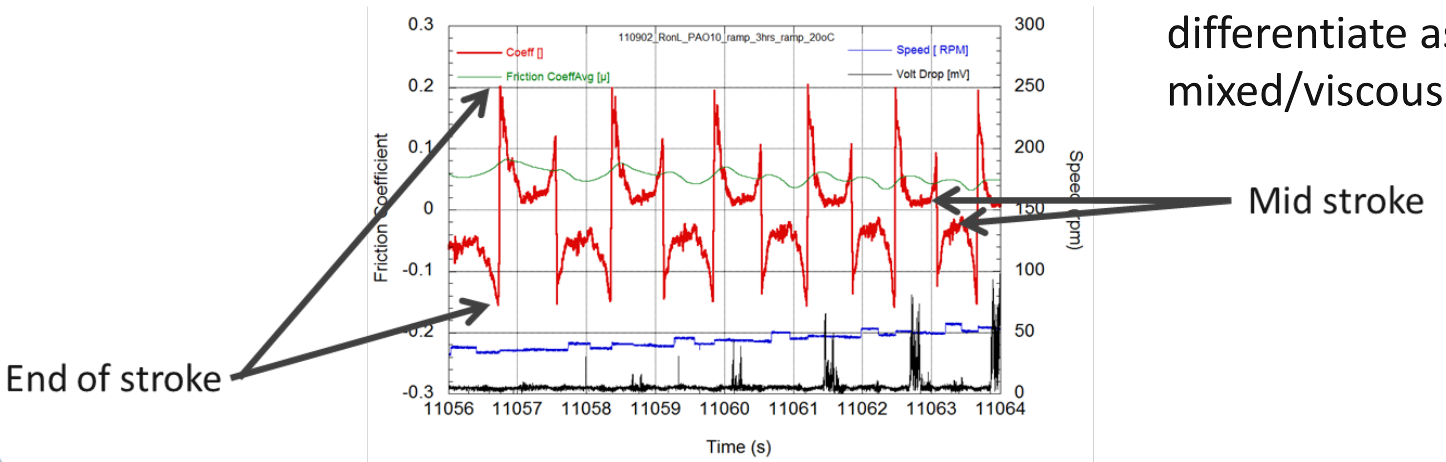
- Real engine operates at high temperatures and high sliding speeds
  - Approximately 10x sliding speed difference (or more) for real engine vs reciprocating rig in “spike” regime
- Ring pushes against liner with force of approximately 482 N/cm max near top-dead-center (TDC). Away from TDC ring forces approximately 11 N/cm.
  - Reciprocating rig load is constant along stroke

The test protocols (time, temperature, and loads) are selected to replicate conditions at TDC where mixed and boundary friction occur. Careful analysis of the friction trace is needed to extract boundary friction - not mixed friction data.

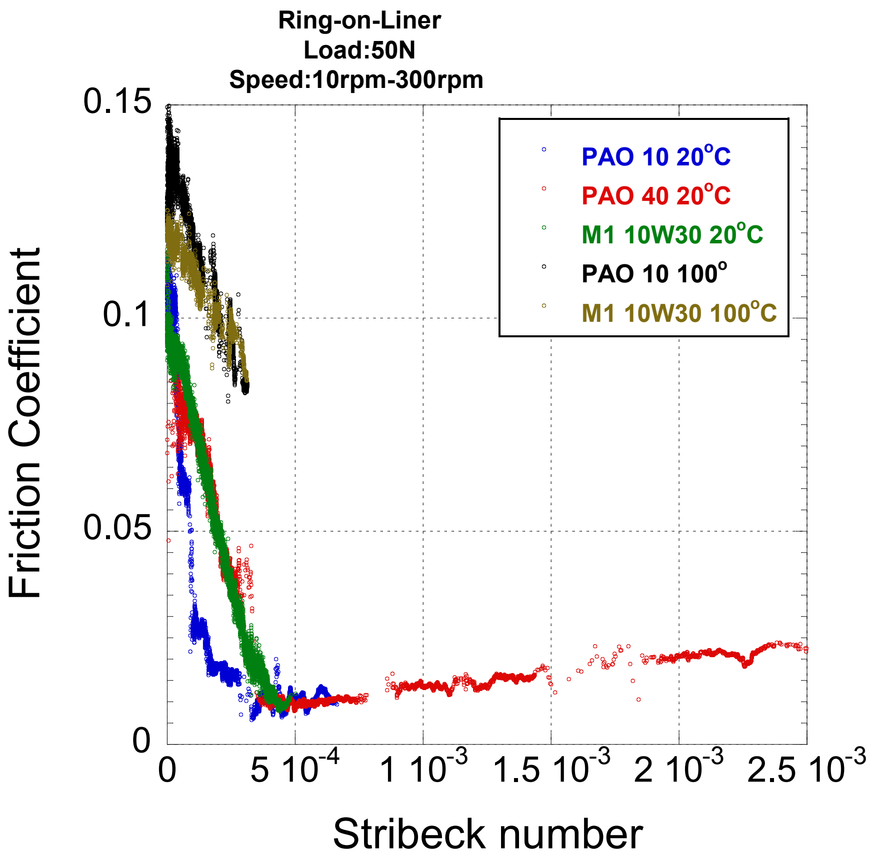


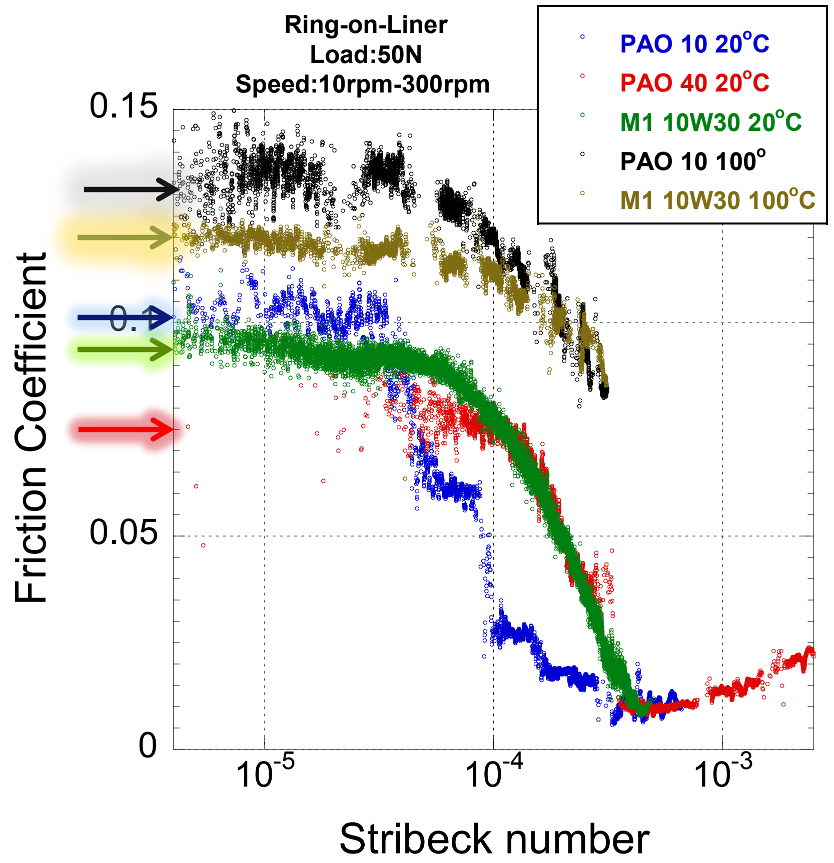
The two graphs at left show "speed ramps" at beginning and end of a long test – note change in friction at the end of the test, indicating formation of a tribofilm and break-in of surface features

The curves in the bottom graph illustrate the ability to differentiate asperity from mixed/viscous friction.



A Stribeck curve has been developed by using experimental friction data. Plotting the data on a linear-log scale accentuates the friction at low Stribeck numbers, i.e., flattens the curve and simplifies extracting the "zero Stribeck" friction coefficient.

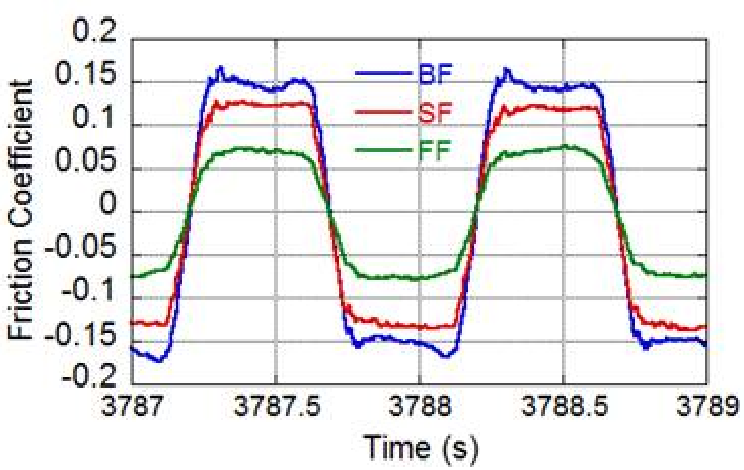




Semi-log presentation simplifies extracting asperity friction at low Stribeck numbers

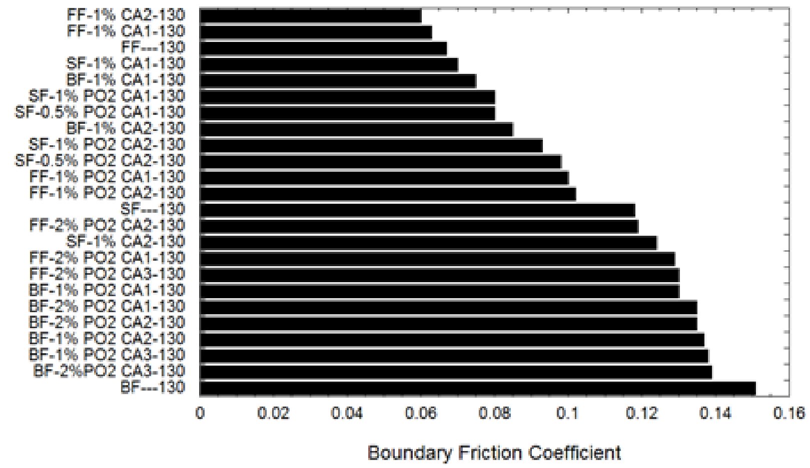
Ring-on-liner tests illustrate the range of boundary friction coefficients one can expect to see. The graph on the left illustrates the friction observed for an unformulated oil, a fully-formulated oil (FF) with a friction modifier (FM), and a FF oil without a FM. Data on the right show the impact of a nano-particle (FM) in base, semi-formulated (SF), and FF oil

$0.07 < \mu_{asp} < 0.15$



- Effect of additives on friction
  - No additive – base fluid only (0.15 @ 100 ^{o}C)
  - FF No FM (0.12 @ 100 ^{o}C)
  - FF oil with FM (0.07 @ 100 ^{o}C)

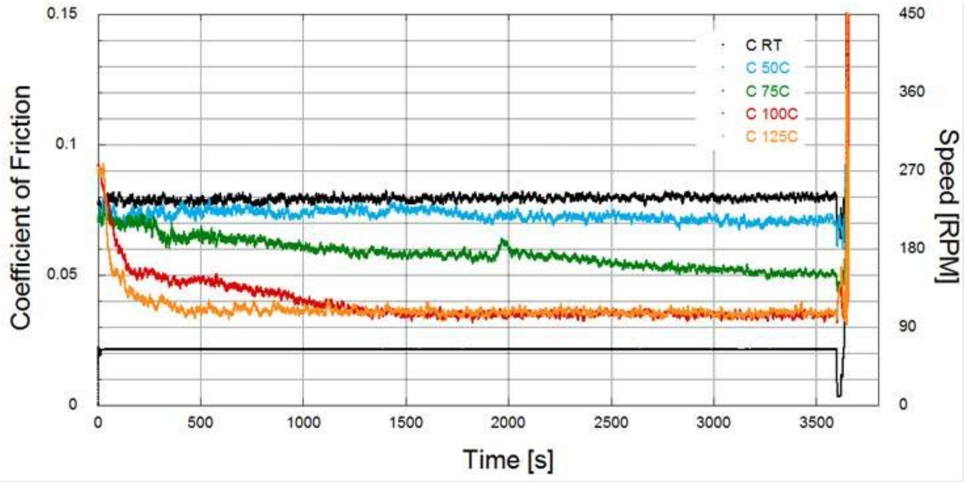
$0.07 < \mu_{asp} < 0.15$



- Effect of nanoadditives on asperity friction
  - Different loading and capping/surfactants
  - Asperity friction ranged from 0.06 to 0.14 (@ 130 C)

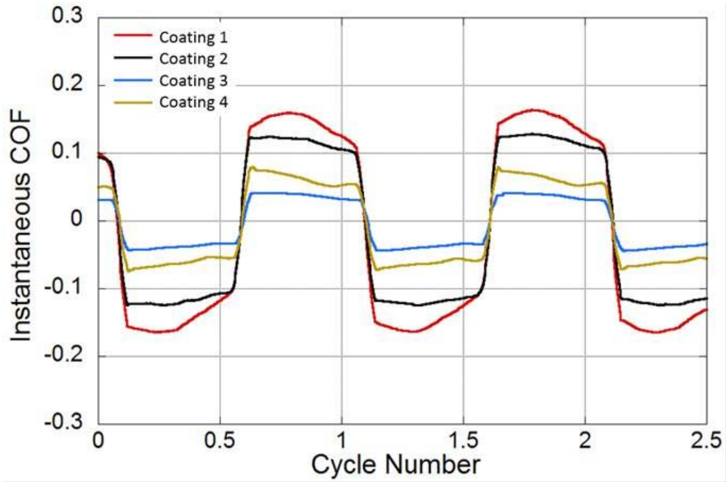
The impact of temperature and coatings on asperity friction is shown below. Image to the left shows the effect of temperature on activating an FM, while the image on the right shows the range of friction when different coatings are applied to power cylinder components.

$0.03 < \mu_{asp} < 0.08$



- Effect of temperature on friction
  - Fully formulated lubricant
  - Factory fill oil, heavy use of friction modifiers
  - Asperity friction ranged from 0.03 to 0.08

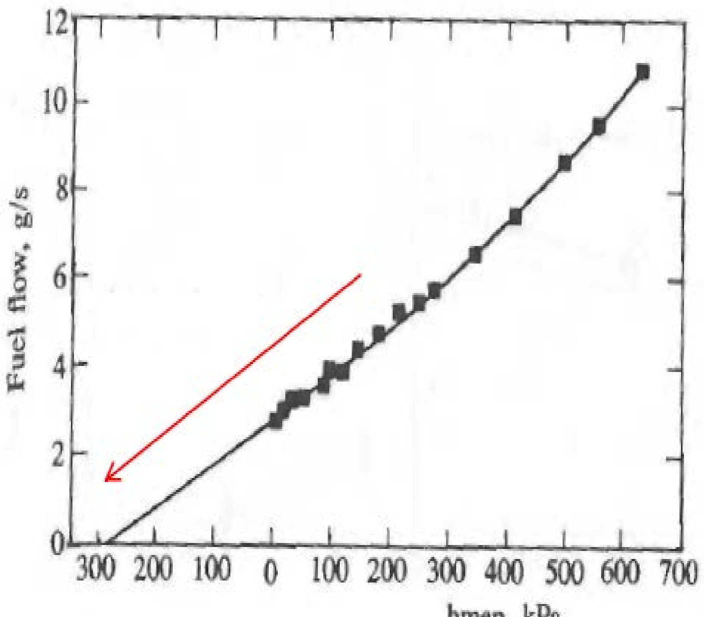
$0.04 < \mu_{asp} < 0.15$



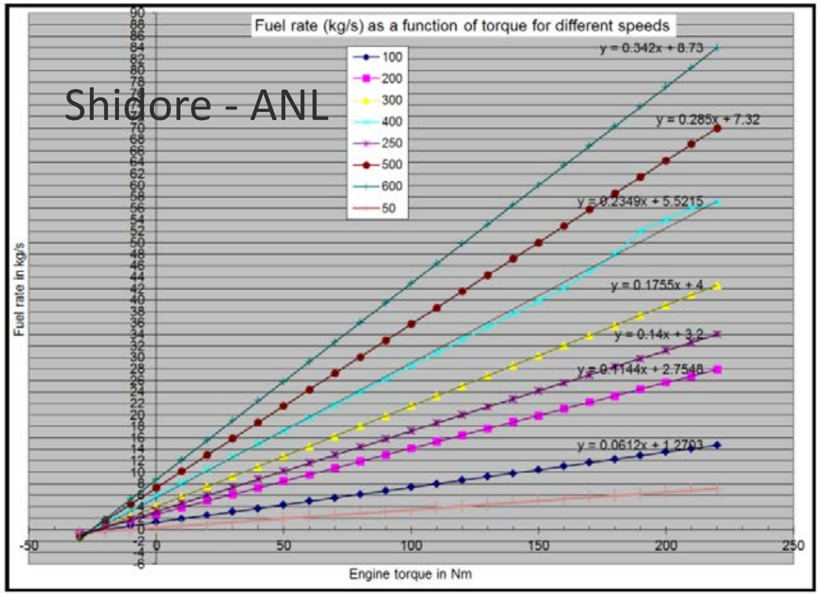
- Effect of coatings on friction
  - 4 different liner coatings
  - Asperity friction ranged from 0.04 to 0.15

Task 3 – Validation: The third task involves validation of the trends using an engine dyno. This activity is planned for FY15. Brake-specific fuel consumption (BSFC) maps for the medium-size diesel engine currently being modeled will be used to validate the trends predicted by the codes.

- A Willan's approach will be used to analyze the data. Extrapolation of the fuel consumption rate down to "zero" will provide information on the FMEP (in this case FMEP includes not only mechanical friction, but also "pumping" friction losses and accessories mechanically connected to the crank).
- Pressure-displacement curves for the BSFC will be provided by the OEM partner.



Heywood, 'Internal Combustion Engine Fundamentals'



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/Truck OEM – NDA protected
- 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)
  - Fuels & lubricants (additives, tribological testing, and characterization)

Summary

- Simulation (Subtask 1)
  - CRADA established, and codes installed and operational
  - Small (500 cc/cylinder) SI engine modeled.
    - Compliant simulation model implemented, and significant portion of test matrix completed.
  - Medium-duty diesel engine model is under development (rigid model implemented).
    - Rigid model and simulation in progress.
    - Compliant model development in progress.
- Asperity Friction (Subtask 2)
  - Protocols established for use of lab-scale rigs to quantify effects of tribological parameters on friction.
  - Protocols established to analyze data to extract isolate asperity friction from mixed and hydrodynamic contributions.
  - Initial data show asperity friction can vary by a factor of 4 or more (0.04 to 0.16).
  - Newer lubricants are trending to lighter viscosities, higher power densities, and higher speeds where boundary lubrication is more dominant, and where information on the effect of FMs and low-friction surfaces will be crucial.

FY14/15 Activities

- Simulation
  - Small (500 cc) SI engine
    - Complete simulation runs / test matrix.
    - Extract regression coefficients for FMEP maps.
  - Medium-duty (1.5 L) diesel
    - Complete rigid simulation of FMEP.
    - Develop 3D mesh for compliant engine model (FMEP simulation using compliant model).
    - Extract regression coefficients.
  - Construction/development of web-based calculator.
  - Integration of FMEP concept into Autonomie
- Friction Database
  - Lab-scale tests to populate asperity friction matrix for the following conditions:
    - PCMO GF5/GF6 lubricants: different brands, viscosities, and temperatures
    - HDDE CJ-4 / PC 11 lubricants: different brands, viscosities, and temperatures
    - Factory fill lubricants
    - Novel basefluids and FMs
- Engine Validation
  - Discussions with ANL and MDDE OEM regarding availability of BSFC data as functions of load, speed, and viscosity