

DOE/DOD Parasitic Energy Loss Collaboration

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Overview

Timeline

■ Project start date	FY 10
■ Project end date	FY 14
■ Percent complete	25%

Budget

■ Total Project Funding	\$450K
— DOE Share	\$450K
— Contractor Share*	\$250K
■ FY 10	\$325K
■ FY 11	\$125K

* TARDEC funding in FY09

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)
- Additive and Lubricant OEMs (NDA)

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%**



Project Objectives - Relevance

- Commercial and military ground vehicles have a number of common issues and concerns related to parasitic energy losses, reliability, and durability.
- Both DOE and DOD have active programs that focus on the development of advanced strategies and technologies to overcome critical barriers.
- Limited DOE/DOD coordination on the development of advanced technologies that can benefit both stakeholders.
- **Project Objectives:**
 - Identify critical barriers related to parasitic friction losses, reliability, and durability common to commercial and military vehicles.
 - Develop and implement advanced tribological solutions (lubricant, materials/coatings, and surface texturing) to reduce fuel consumption.
 - Establish DOE/DOD collaboration that utilizes key facilities and expertise to investigate, model, and understand fundamental tribological phenomena that impact fuel efficiency, reliability, and durability.
- **Goal** – Improve vehicle fuel efficiency while maintaining/improving reliability and durability.



Relevance - Fuel efficiency is a common concern for civilian and military sectors. Advanced low-friction technologies can enable reductions in 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/gal.

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

Military Vehicles in Combat

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.



Relevance - Reliability/Durability Challenges

■ Commercial Vehicles (DOE)

- Implementation of emission control technologies
 - After-treatment devices require development of low-SAPS lubricants
 - Use of exhaust gas recirculation introduces higher levels of soot and combustion products into lubricants
- Development of alternative-fuel vehicles
 - Lubricity of alternative, non-petroleum-based fuels
 - Fuel dilution of lubricants
- Downsizing and weight reduction of vehicle components
 - Increased power density/stresses on critical engine and drivetrain components
 - Poor tribological properties of lightweight materials

■ Military Ground Vehicles (DOD)

- Accelerated failure of ground vehicles in Southwest Asia - extreme tribological environments
 - High temperatures – rapid degradation of lubricant properties
 - Sand/grit – accelerated wear of critical engine and drivetrain components
 - Vehicles must also function in arctic temperatures – poor flowability
- Loss-of-lubricant incidents
 - Survivability of engine, drivetrain, and other mission-critical components when lubricant supply is non-functional
- Multi-function lubricants
 - Common lubricants for transmission and engine applications
 - Compromised performance to achieve commonality in fluids

Common need to improve reliability and durability of lubrication systems



Milestones

■ FY 2010

- Established collaborative project on parasitic losses with DOD/TARDEC.
 - Focus on fuel efficiency.
- Conducting discussions with industry (in progress).
 - Component OEM – Focus on compression ring and oil control ring at low loads – to focus on simulating hydrodynamic regime where viscous losses are greatest.

■ FY 2011

- Model impact of low-friction strategies on vehicle efficiency – commercial and military ground vehicles (ongoing).
 - Obtain input on “typical” driving schedules (commercial vs. military).
 - Apply driving schedules (engine maps) to predict changes in friction mean effective pressure (FMEP).
 - Scale fuel economy to indicated mean effective pressure (IMEP).
- 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 (\approx to 1 N/mm).
 - **Durability/Reliability** – Maximum forces occur near top-dead-center where boundary/mixed regimes dominate – focus on high loads (\approx 50 N/mm).



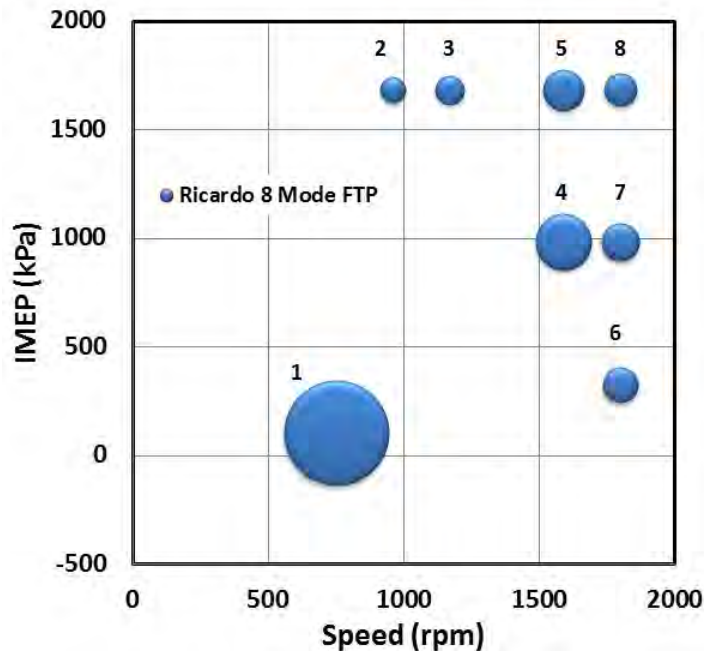
Approach/Strategy - Model parasitic losses to identify magnitude of impact and general approach, and identify pathway(s) to improve fuel consumption using lab-scale rigs.

- Parasitic friction losses are modeled using advanced mechanistic-based codes—provides guidance on the magnitude of asperity and hydrodynamic losses at different engine conditions.
 - PISDYN models boundary and viscous losses between piston and liner.
 - RINPAK models boundary and hydrodynamic viscous losses between rings and liner.
 - VALVDYN models asperity and viscous losses of valvetrain components.
 - ORBIT models viscous and asperity losses in bearings.
- Utilize advanced lab-scale test facilities to evaluate candidate solutions that can lower parasitic friction losses – provides input on the magnitude of reductions one can realistically expect at different conditions.
 - Lubricants
 - Materials
 - Engineered Surfaces
- This project is coordinated with other DOE vehicle technology projects on boundary lubrication, hard coatings, and advanced lubricants.

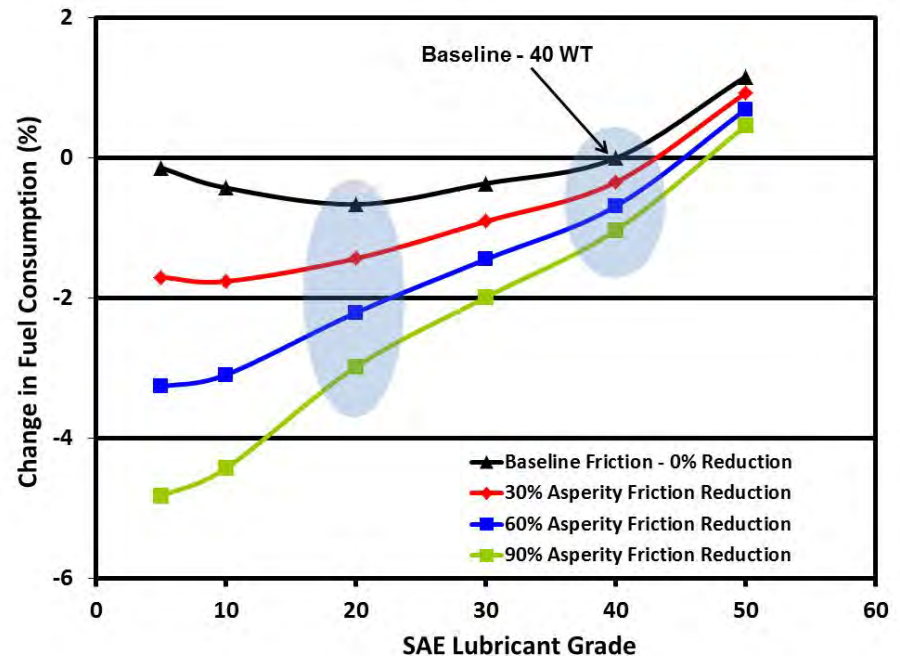


Accomplishment - Prior activities modeled parasitic friction losses to determine potential impact on fuel efficiency.

- Model FMEP as a function of boundary lubrication and lubricant viscosity at different engine conditions (speed and load).
 - PISDYN, RINGPAK, ORBIT, VALVDYN
- Adjust fuel consumption rate at each condition for changes in the FMEP vs. baseline assumptions.
- Apply weighting factors to compensate for desired driving cycle.
- Predict change in fuel consumption for specific driving cycle as a function of change in boundary friction and lubricant viscosity.



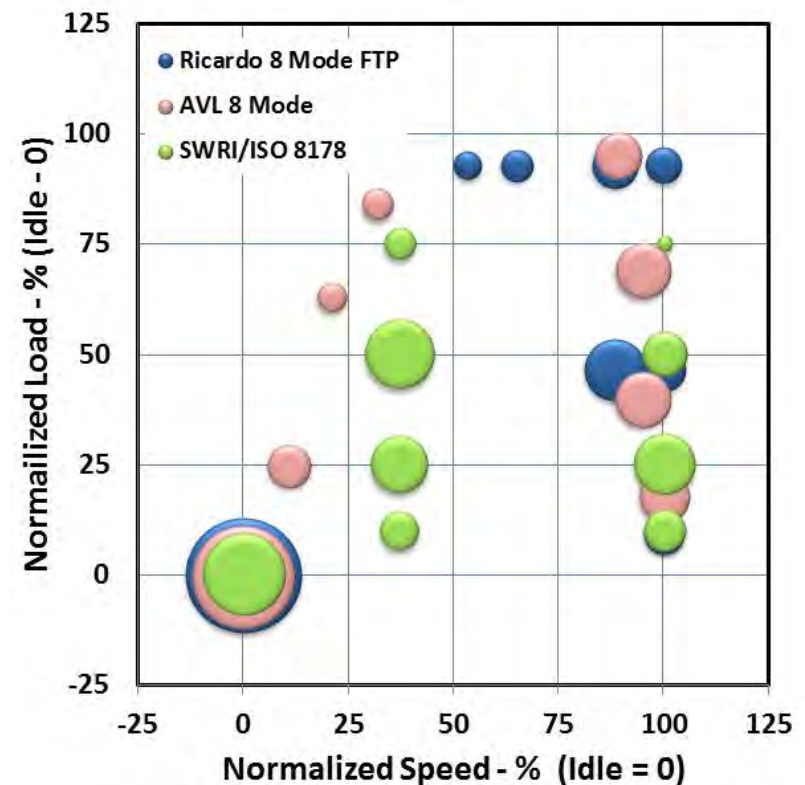
Ricardo 8-Mode Federal Test Procedure (FTP) Cycle –
Size of circles proportional to weighting factor



Predicted change in fuel consumption as a
function of friction and lubricant viscosity

Accomplishment (cont'd) - Current activities identify differences in military and civilian driving cycles and impact on fuel efficiency.

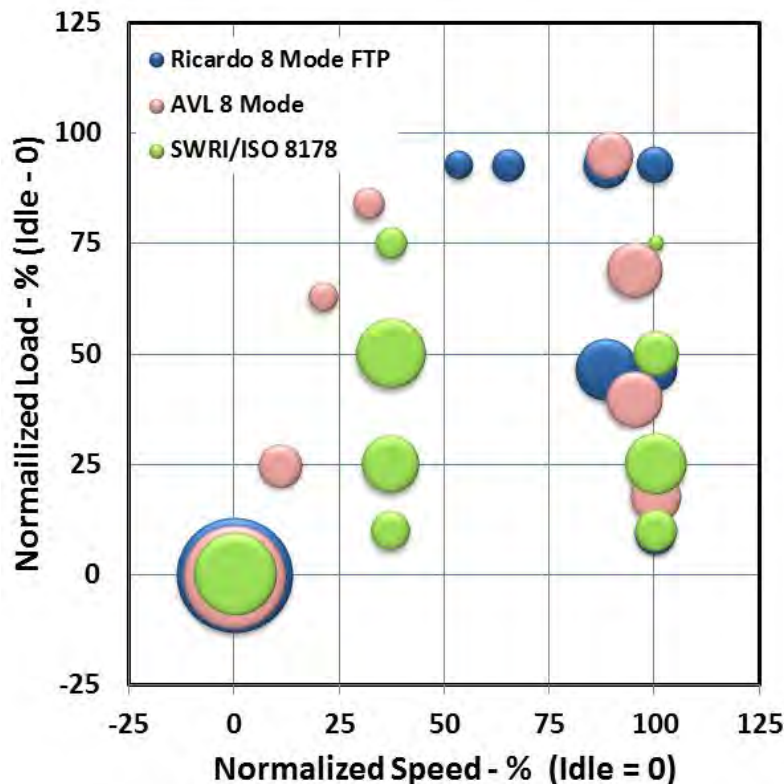
- Predicting impact of parasitic friction on vehicle efficiency of military vehicles requires knowledge of engine mode(s) and weighting factors.
- Military drive cycles differ from commercial, on-road, and off-road cycles – different engine modes and different weighting factors.
- Unique military drive cycles include on-road and off-road functions:
 - Tactical idle
 - Convoy escort
 - Cross-country
 - Urban assault
- Commercial drive cycles involve primarily on-road cycles:
 - Passenger cars – urban, highway
 - Heavy vehicles – highway, urban
 - Utility, delivery cycles
 - Hybrid, plug-in hybrid cycles



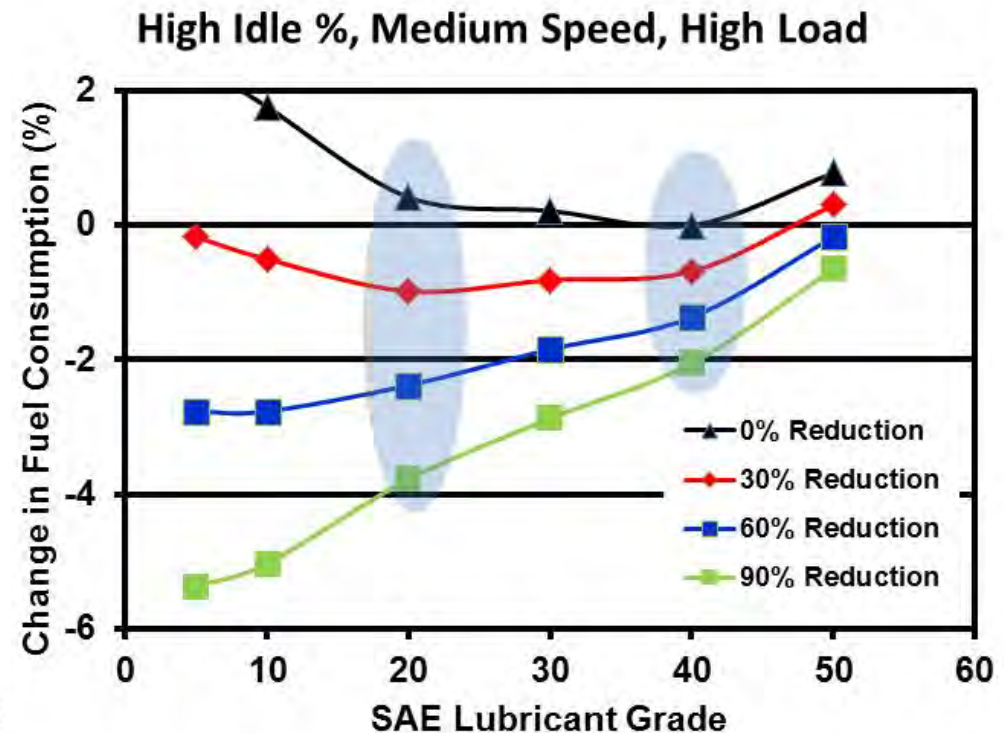
Comparison of Engine Operation Modes between Commercial and a Specific Military Cycle

Accomplishment (cont'd) - Current activities demonstrate potential impact of different driving cycles and impact on fuel efficiency

- The impact of low friction technologies on fuel economy for different driving cycles is not obvious



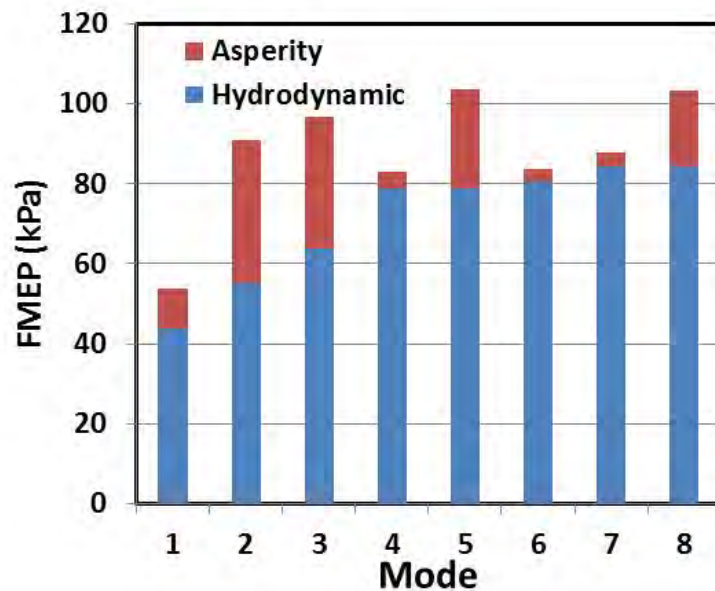
Comparison of Engine Operation Modes between Commercial and Specific Military Cycle



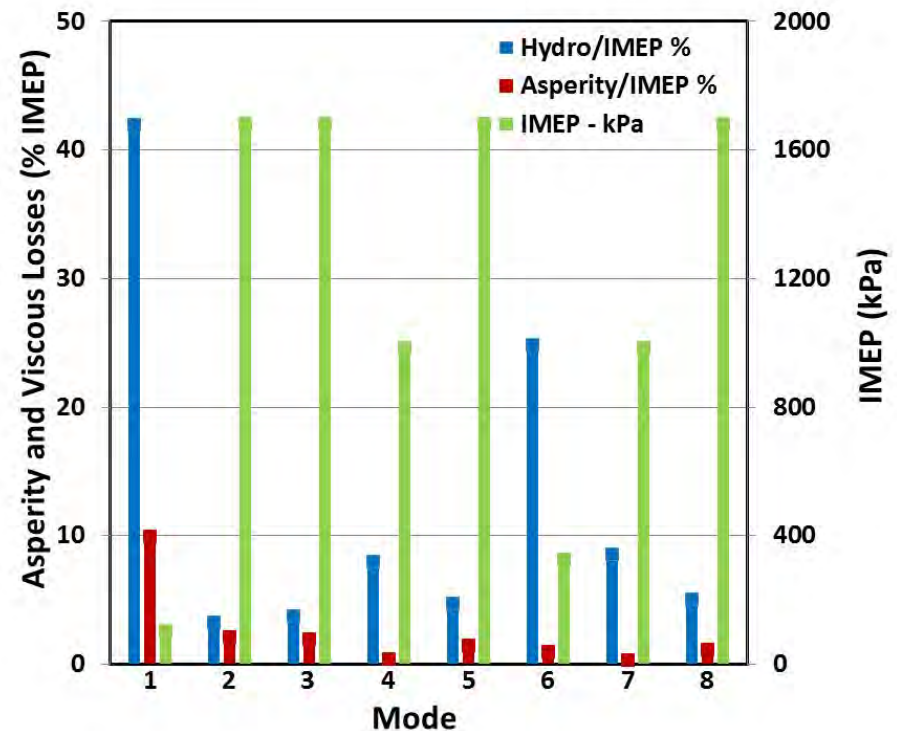
Predicted Impact of Friction Reduction Technologies on Fuel Consumption (high-idle, medium-speed cycle)

Accomplishment - Analysis of Ricardo 8-mode FTP cycle shows that while FMEP is relatively constant, its relative ranking as percentage of IMEP varies significantly.

- Analysis of Ricardo FMEP data revealed high-load modes exhibit high asperity FMEP.
- Total FMEP is relatively constant (80 to 100 kPa).



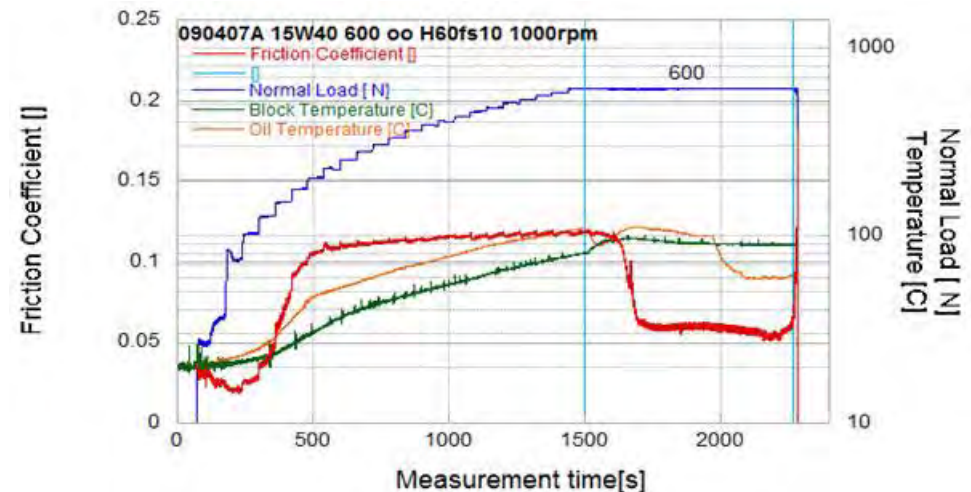
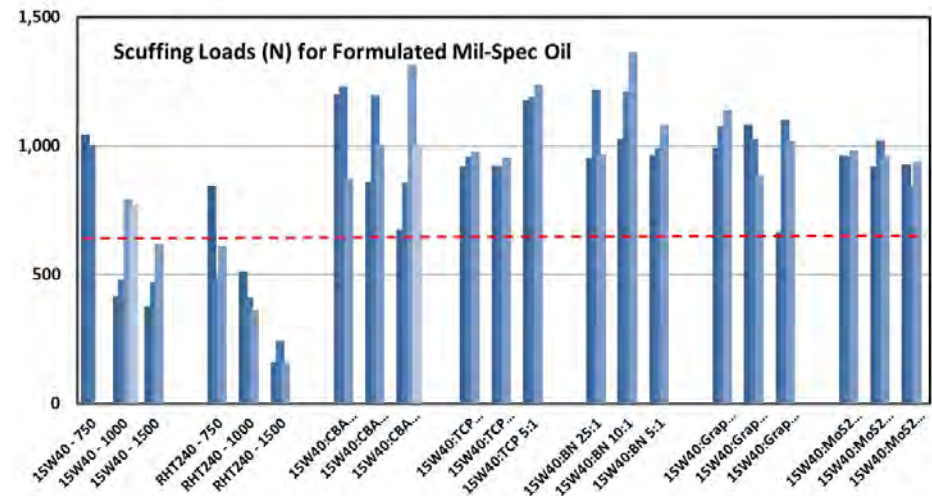
FMEP at Each Mode for Baseline (40WT) Condition



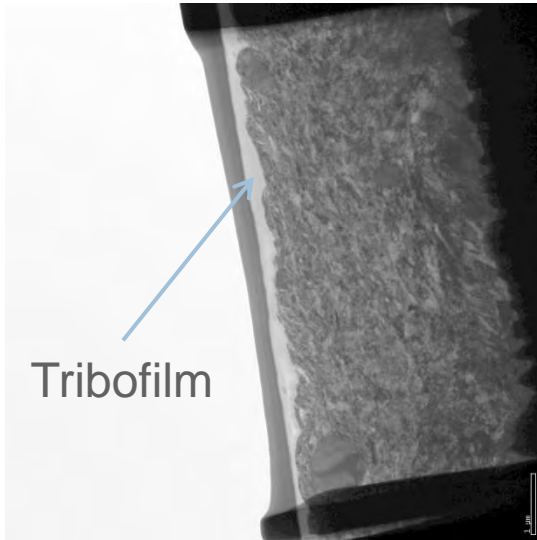
Asperity and Viscous Friction and Total IMEP as Function of Engine Mode

Accomplishment - Characterization of low-friction tribofilm formation during oil-off tests - Additives can significantly impact reliability and performance under starved lubrication.

- Block-on-ring studies identified impact of additives on scuffing resistance of oils with additives.
- Oil-off simulation revealed formation of low-friction tribofilms that would not scuff.

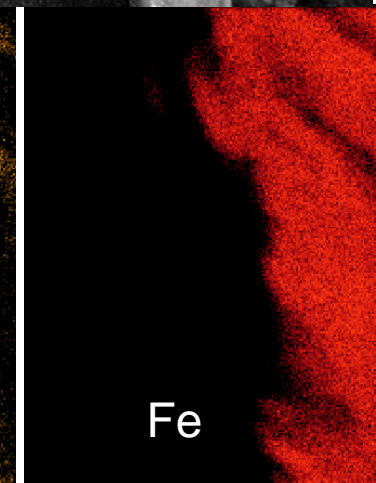
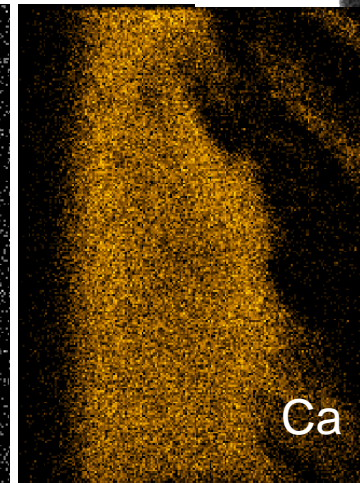
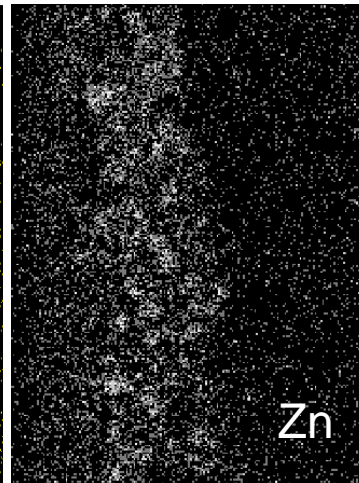
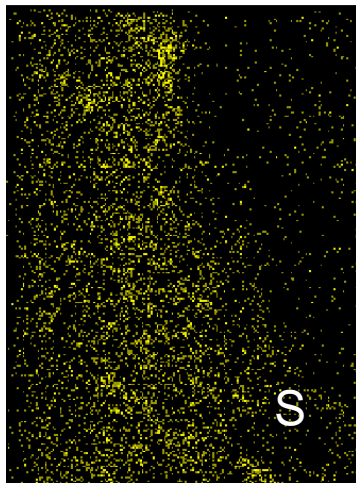
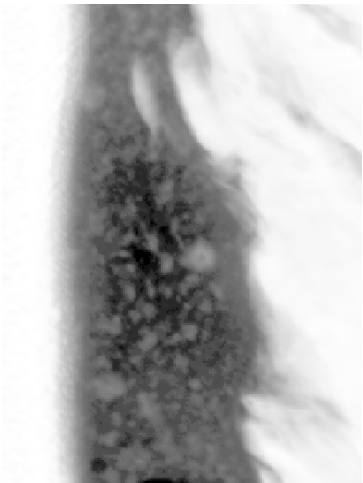
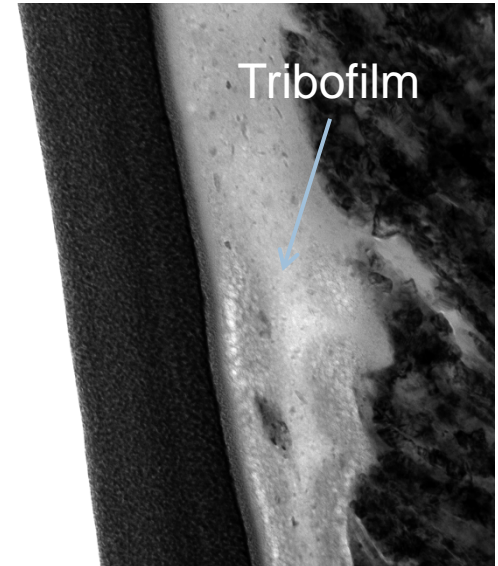


Accomplishment - Transmission electron microscopy (TEM) and focused ion beam spectroscopy (FIBS) mapping of low-friction, scuff-resistant additive.

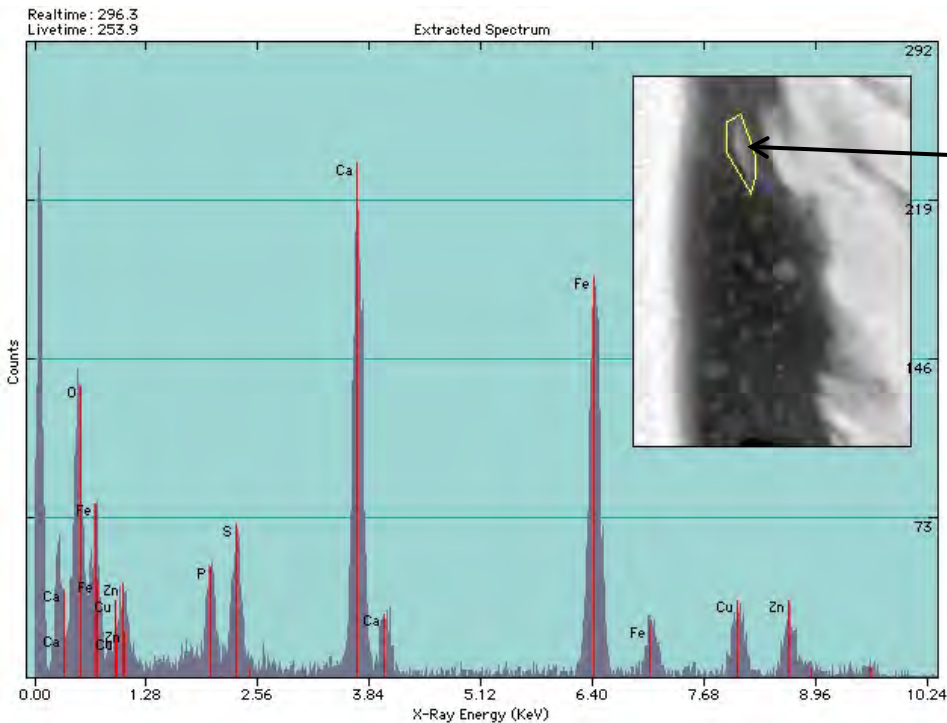


Detailed chemical analysis of TEM cross sections revealed **heterogeneous distribution of additive elements** in tribofilms.

(Ajayi, Lorenzo-Martin, Zaluzec)

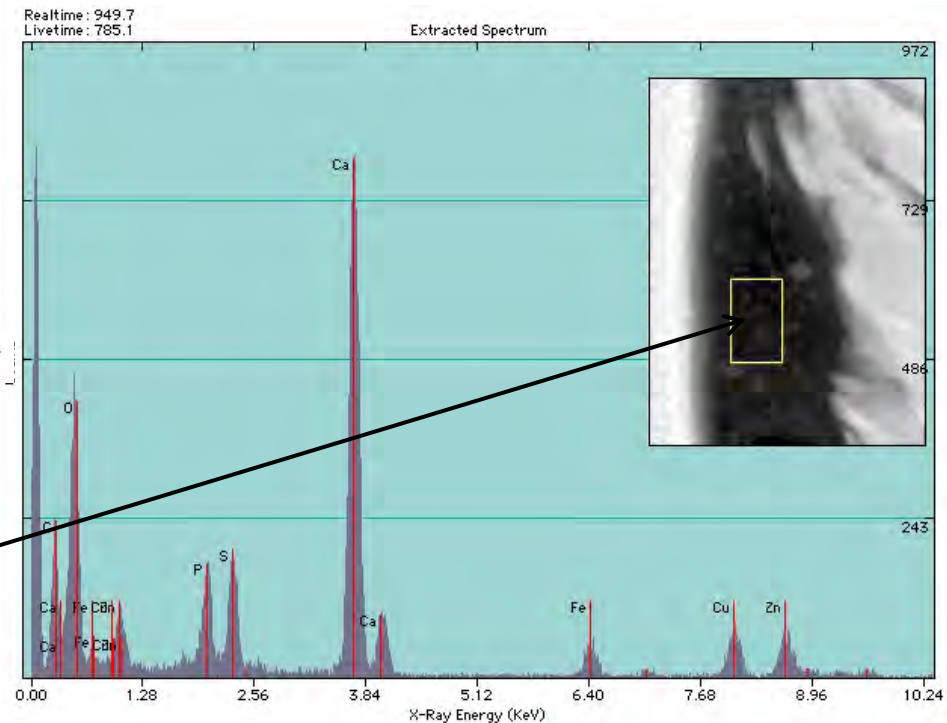


Accomplishment - Point-by-point collection of X-ray energy spectrum enables post-TEM analysis of discrete regions of interest in protective tribofilms - assist in development of friction models.



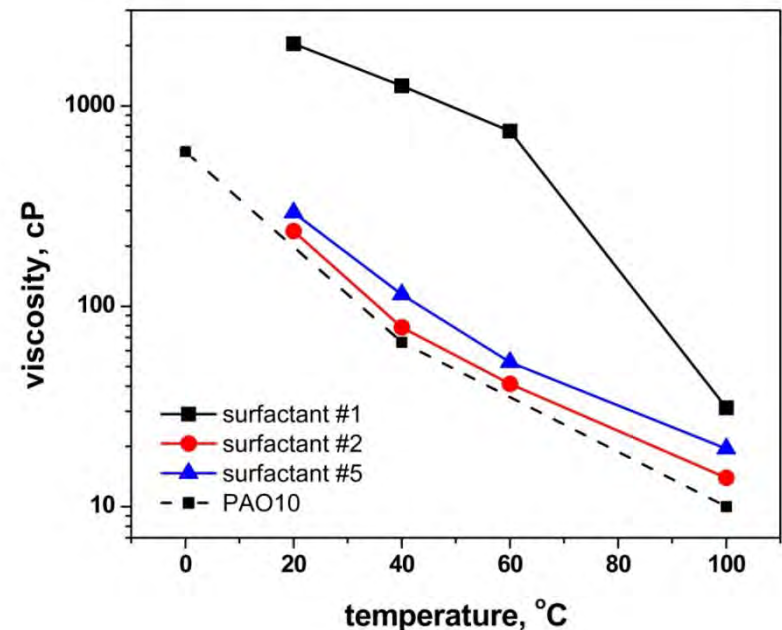
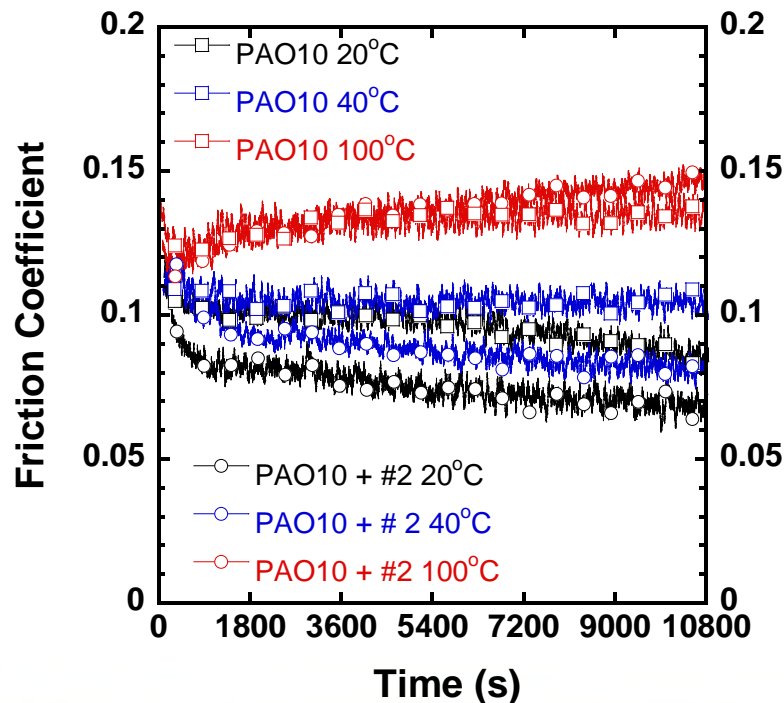
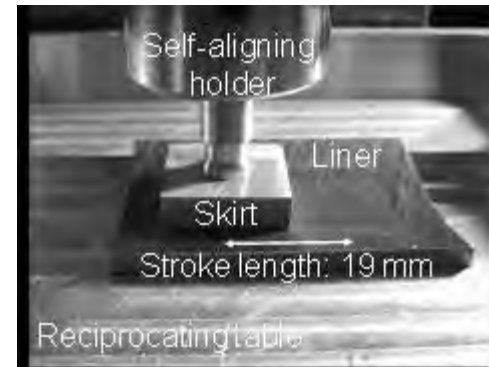
X-ray spectrum of particle in tribofilm

X-ray spectrum of background in tribofilm



Accomplishment - Lab-scale simulation and characterization of base lubricant with nano BN additive.

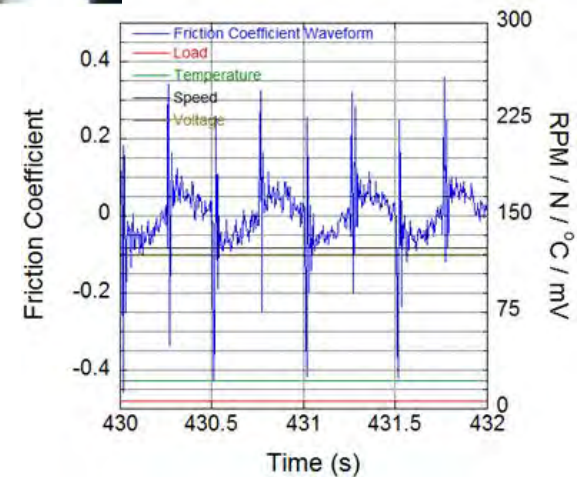
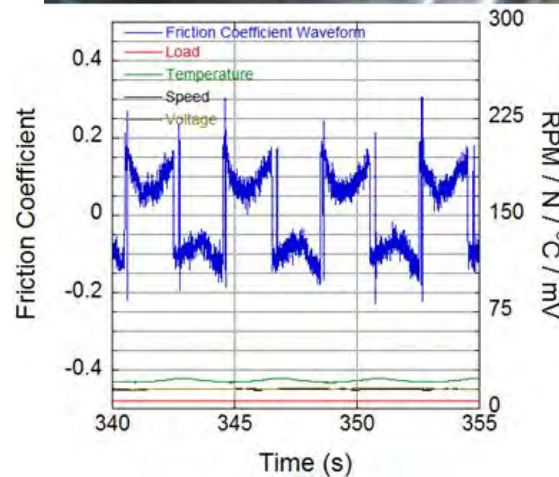
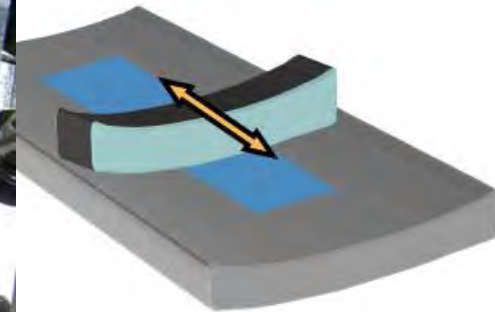
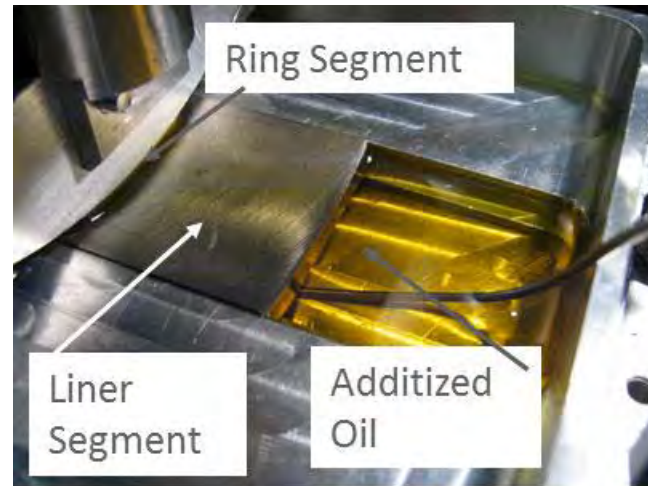
- Reciprocating skirt-on-liner configuration was used to examine impact of nano BN additive on friction and wear.
- Tests at different temperatures indicated nano BN additive reduces friction and wear.
- Reduced friction influenced by lower asperity friction and increased viscosity



Timofeeva, Demas, and Routbort

Accomplishment - Lab-scale simulation and evaluation of friction response of commercial lubricants and surface finishes.

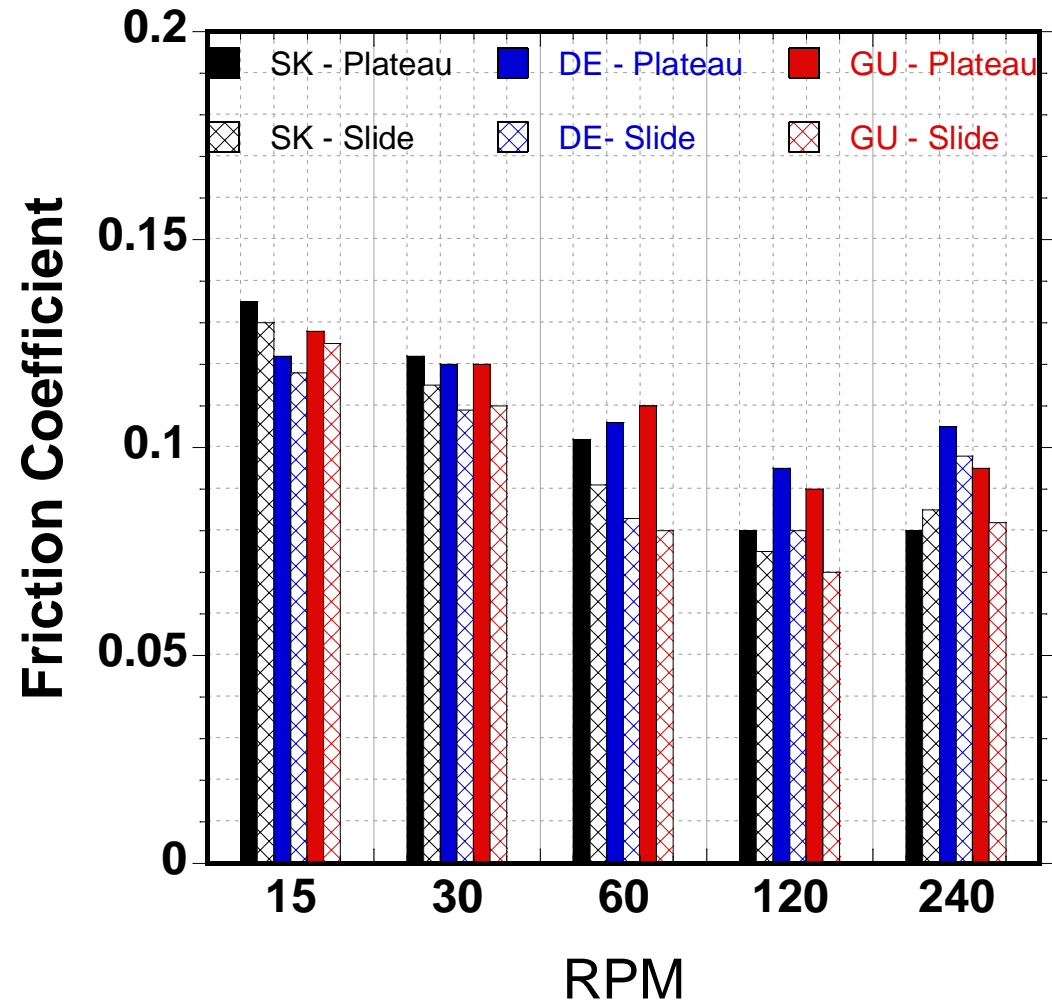
- Performed ring-on-liner tests to examine:
 - impact of liner finish (plateau hone vs. smoother slide-honed liners) on ring-liner friction
 - variation in friction from different brands of oil (formulated 15W/40)
- Modified protocol to examine friction under light loads ($< 1 \text{ N/mm}$) that are more representative of “crank-angle” average loads.



Able to replicate boundary, mixed, and hydrodynamic friction regimes.

Accomplishment - Examined impact of surface texture and lubricant “brand” on friction.

- Low-load, reciprocating tests performed to examine potential impact/variations in friction behavior:
 - Variations within a 15W/40 lubricant
 - Variations in surface finish (liner)
- Plateau vs. slide honing:
 - Smoother, slide-honed finish reduced cycle-averaged friction
 - Brand-to-brand impact depends on test temperature
 - No consistent improvement in friction – ranking depended on test temperature



Collaborations/Coordination with Other Institutions

- Project involves collaborations with the following institutions to evaluate low friction (fuel efficiency) and durability/reliability:
 - DOD/TARDEC [government] – 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
 - DOD Ground Vehicle OEM [industry]- Provide guidance on vehicle needs/requirements and drive cycles.
 - Engine component supplier [Mahle - industry]– Provide prototypic engine components.
 - Rings, pistons, & liners
 - Modeling of friction and wear during benchtop 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), Propulsion Materials (coatings), and Fuels & Lubricants (additives)
 - Collaborative efforts with MIT Lubrication Consortium



Proposed Future Work

- Model impact of low-friction strategies on vehicle efficiency – commercial and military ground vehicles.
 - Obtain input on “typical” driving schedules (commercial vs. military).
 - Apply driving schedules (engine maps) to predict changes in FMEP.
 - Scale fuel economy to IMEP.
- Evaluate the impact of candidate low-friction technologies (additives, component materials/coatings, and surface texture) on friction, wear, and scuffing performance.
 - Benchtop friction and wear tests using ring/skirt-on-liner tests
 - Benchtop scuffing tests - four-ball and block-on-ring configurations
 - Comparison of baseline vs. advanced candidate technologies
 - Surface finish (plateau honing vs. slide honing)
 - Baseline mil-spec and commercial lubricant vs. advanced additized lubricants)
 - Characterization of field-tested lubricants (commercial and military)
 - Validation of friction/wear modeling software (Mahle Virtual Tribology Laboratory)
 - Prediction of friction and wear performance based on surface texture and lubricant rheological properties
- Establish test program with TARDEC/Vehicle OEM to validate advanced concepts on engine/drivetrain simulation rigs.



Summary

- Established collaborative project with TARDEC and DOD vehicle contractors to identify potential impact of low-friction technologies on fuel economy of on-road and military vehicles.
- Approach – Research conducted in laboratory settings, using advanced benchtop rigs to quantify tribological properties of candidate technologies (lubricants, additives, coatings, and surface texture). Measurements of friction, wear, and scuffing resistance. Detailed characterization of tribofilm formation leverages Boundary Layer Lubrication Project.
- Technical Accomplishments – Preliminary studies on scuffing performance of mil-spec lubricants have identified two candidate additives that enhance the formation of low-friction tribofilms that are scuff-resistant. Demonstrated application of FIBS to characterize structural and chemical make-up of tribofilms.
- Collaborations – Coordination and collaboration of the project with key parties and co-sponsors: TARDEC – Fuels and Lubrication Technical Team, Heavy-Vehicle OEM*, Component Supplier (Mahle), and Lubricant OEMs*.

* Names withheld subject to non-disclosure agreements.