Lubricant Formulations to Enhance Engine Efficiency (LFEEEE) in Modern Internal Combustion Engines:

Project ID FT019

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Sloan Automotive Laboratory
Cambridge, Massachusetts
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Agenda

I. Objectives

II. Background and Approach

III. Accomplishments
   1. Power Cylinder Modeling
   2. Valve Train Modeling/Experiment
   3. Engine Experiment

IV. Conclusions
“Investigate, develop, and demonstrate low-friction, environmentally-friendly and commercially-feasible lubricant formulations that would significantly improve the mechanical efficiency of modern engines by at least 10% (versus 2002 level) without incurring increased wear, emissions or deterioration of the emission-aftertreatment system”
Lubricant Formulations for Enhanced Engine Efficiency (LFEEEE)

• DOE Vehicle Technologies (VT) Program
  – 3 year
  – 3 grad students
  – Industry Partners
    • Infineum
    • Kohler
    • Cummins Filtration

• Related Projects
  • Supertruck
Phases – LFEES (Lubricant Formulation to...)

**Phase 1:**
Investigate ideal formulations tailored to each major subsystem for best performance

**Phase 2:**
Investigate composite formulations for combined system

**Phase 3:**
Demonstrate mechanical efficiency improvement for best formulation over a range of operating conditions
# Project Timeline

**Lubricant Formulations to Enhance Engine Efficiency in Modern Internal Combustion Engines**

DOE-NETL Cooperative Agreement #DE-EE0005445

**Massachusetts Institute of Technology**

**Project Start Date:** Oct 1, 2011

**Proposed Project Completion:** Sep 30, 2014

## Phase 1: Best Lube Formulations for Subsystem

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<td>1.0</td>
<td>Develop Project Management and Planning</td>
<td>M1</td>
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<td>2.0</td>
<td>Model Lubricant Effects on Individual Sub-Systems</td>
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<td>2.1</td>
<td>- For piston, ring, liner sub-system</td>
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<td>2.2</td>
<td>- For valve train sub-system</td>
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<td>3.0</td>
<td>Develop Lube Test Parameters w/ Industry Partners</td>
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<td>4.0</td>
<td>Perform Parametric Experiments on Lube Effects</td>
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<td>5.0</td>
<td>Data Analysis, Interpretation and Design Iterations</td>
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**MILESTONE 1 (M1):** Modeling Power Cylinder
**MILESTONE 2 (M2):** Modeling Valve Train
**MILESTONE 3 (M3):** Develop Candidate Matrix
**MILESTONE 4 (M4):** Modify/Prepare Test Engine
**MILESTONE 5 (M5):** Instrument Diagnostics
**MILESTONE 6 (M6):** Parametric Lube Effect Tests
**MILESTONE 7 (M7):** Tests with Floating Liner Engine

## Phase 2: Best Composite Formulations for Combined System

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<td>6.0</td>
<td>Model Lube Formulations with Regional Variations</td>
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<td>7.0</td>
<td>Test, Optimize Composite Oil Formulations</td>
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<td>7.1</td>
<td>For Segregated Power-cylinder, Valve Train Subsystems</td>
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<td>7.2</td>
<td>For One-Oil Fully Mixed Combined System (Baseline)</td>
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<td>7.3</td>
<td>For Regional (Local) Modulation of Lubricant Properties</td>
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<td>8.0</td>
<td>Develop Practical Means to Implement New Formulations</td>
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**MILESTONE 8 (M8):** Model Variable Lube Formulations
**MILESTONE 9 (M9):** Parametric Lube Tests, one oil, full mixing
**MILESTONE 10 (M10):** Parametric Lube Tests, one oil, segregated
**MILESTONE 11 (M11):** Parametric Lube Tests, with local modulation

## Phase 3: Proof of Concept, Final Demonstration

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<td>9</td>
<td>Demonstrate Final Lube Formula in Full System</td>
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<td>10</td>
<td>Evaluate &amp; Test Impact on Aftertreatment Systems</td>
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**MILESTONE 12 (M12):** Full Demonstration, Optimized Oil
**MILESTONE 13 (M13):** Aftertreatment Impact Assessment

## All Phases: Throughout project

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<tr>
<td>11</td>
<td>Review lube formulation iterations with industry</td>
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<td>12</td>
<td>Periodic formal reviews &amp; reports</td>
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<td>- Deliver annual reports</td>
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<td>- Deliver Final Report</td>
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Background - Functions of lubricant/additives:

1. **Base Oil:** API Groups: I, II (low S), III (low S, high VI), IV: synthetic, V other

2. **Additives:**
   - Detergents
   - Dispersants
   - Anti-Wear
   - Anti-oxidants
   - VI and Friction Modifiers
   - Anti-foam
   - Pour-point depressants
   - Extreme-pressure wear, etc
Background - Functional Requirements

• **Valvetrain**
  – High EHD pressures (~2000 MPa)
  – Low Temp
  – No combustion gas/soot
  – No path to tailpipe

• **Power Cylinder**
  – Predominantly hydro
  – High Temp (rings ~250°C)
  – Hostile (acidic) environment
Friction (Top Ring, Skirt), Position & Temperature Domain

**Temperature vs Liner Position**

- Distance from Top Ring TDC [mm]
  - Temp [°C]
  - 80, 100, 120, 140, 160, 180, 200, 220

**Viscosity vs Temperature**

- Distance from Top Ring TDC [mm]
  - Temp [°C]
  - 80, 120, 160, 200

**Instantaneous Power Loss vs Position, 15W40, A100**

- Instantaneous Power Loss [W]
  - 0, 50, 100, 150, 200, 250, 300
- Temperature [°C]
  - 80, 120, 160, 200
Optimizing –Upper and Lower Temperature Viscosity vs Friction and Wear

RING Peak Wear vs Friction Loss

Total Friction Loss (W)

Peak Wear Factor (W)

VM1
VM2
15W40
VM3
VM4
Optimizing –Upper and Lower Viscosity vs Friction and Wear

RING Peak Wear vs Friction Loss

Total Friction Loss (W)

- VM1
- VM2
- VM3
- VM4
- 15W40

Peak Wear Factor (W)

- 800
- 850
- 900
- 950
- 1000
- 1050
Optimizing –Upper and Low Viscosity vs Friction and Wear

![Graph showing total friction loss and peak wear factor for VM1, VM2, 15W40, VM3, and VM4 across different temperatures.](image-url)
Viscosity vs Temp design parameters for $\eta_{\text{mech}}$
Vaporization/Friction Models

Oil Film Thickness vs Position, 15W40, A100

- TDC Top Ring
- TDC Second Ring
- TDC Oil Control Ring

Dist from Top Ring TDC [mm]

Film Thickness [μm]

Intake
Power
Vaporization/Friction Models

**Avg Molecular Weight vs Position, 15W40, A100**

![Graph showing average molecular weight vs position with data points.]

**Viscosity vs Position, 15W40, A100**

![Graph showing viscosity vs position with lines for No Vap and Vap conditions.]  

+ 1.1% total top ring friction  
-15.0% boundary friction  
+ 1.6% hydrodynamic friction  
-17.0% wear factor
Inspired strategies:

• Lubricant formulation strategy – maintain temp, vary lubricant:
  – Developing optimal power cylinder lubricant with Infineum/DDC
  – Presence of heavy component may provide wear benefit and allow lower viscosity midstroke

• In situ control strategy – maintain lubricant, vary temperature
  – (Supertruck program efforts)
Power Cylinder modeling -
Accomplishments/Looking Forward

Publications:


Acknowledgements

This work was supported by Cooperative Agreement DE-EE0005445 from the U.S Department of Energy. We gratefully thank our project sponsors, Dr Steve Przesmitzki and project monitor Nicholas D’Amico, for their support. We also appreciate the many helpful interactions with, and insights from, Dr Jai Bansal and Maryann Devine of Infineum, and our other program partners with whom we periodically exchanged ideas.
Valvetrain Temperature Dependence

• Valve Train modeled with GT Suite
• Experimental Bench Tests
Significant boundary friction identified at low speed in actual system

Total Friction - Benefit from Lower Temperature and Decreased Shear Thinning

25%
Valvetrain Studies - Accomplishments/Looking Forward

• Inspired strategies:
  – In absence of fuel system, significant boundary friction at low speed
    • Reduce shear thinning (developed pure Newtonian SAE 40)
    • Reduce temperature (split lubricating system option)

• Presentations:
  – Plumley, Wong, Devine, Bansal. “Analysis of shear-thinning on engine friction using mineral and PAO base oils” *STLE 2014 Annual Meeting*
Split System Engine Tests

- Diagnostic tool
Slight total engine friction benefit with lower multigrade in power cylinder
Slight Total Mechanical Efficiency benefit with lower multigrade in power cylinder
Oil Aging - NEW40 sample, 8 hours in test engine

New Valve Train Power Cylinder
Whole Engine Studies-
Accomplishments/Looking Forward

• Accomplishments:
  – Established working split system prototype
  – Demonstrated split system benefit with base oils

• Presentations:
  – Plumley, Wong, Devine, Bansal. “Analysis of shear-thinning on engine friction using mineral and PAO base oils” *STLE 2014 Annual Meeting*
SUMMARY – Milestone Progress

• M1: Initial modeling power-cylinder  
• M2: Initial modeling Valve Train  
• M3: Initial spec for test matrix w/ industry  
• M4: Modify engine for split system  
• M5: Diagnostic instruments on test engine  
• M6: Parametric Effects Tests  
• M7: Floating liner test  

↑ = milestone reached
SUMMARY – Milestone Progress

• M8: Model local variable formulations
• M9: Parametric Tests, one oil, full mix
• M10: Parametric Lube Tests, one oil, split
• M11: Parametric Lube Tests, 2 oils, split
• M12: Full Demo, Optimized Oil – (July ‘14)
• M13: Aftertreatment Impact Assessment – (July ‘14)
• The research team has identified and formulated lubricants that optimize the power cylinder friction
• The research team has identified and formulated lubricants that optimize the valvetrain friction
• The benefit (lower overall engine friction) of the split lubricant circuits has been demonstrated
• All scheduled milestones were met