

DOE-NETL Cooperative Agreement #DE-EE0005445



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

Project ID FT019

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Sloan Automotive Laboratory Cambridge, Massachusetts June 19, 2014



This presentation does not contain any proprietary, confidential, or otherwise restricted information

Agenda

Objectives

II. Background and Approach

III. Accomplishments

- Power Cylinder Modeling
- 2. Valve Train Modeling/Experiment
- 3. Engine Experiment

IV. Conclusions



Project Objective

"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 (LFEEE)

- DOE Vehicle Technologies (VT) Program
 - 3 year
 - 3 grad students
 - Industry Partners
 - Infineum
 - Kohler
 - Cummins Filtration
- Related Projects
 - Supertruck

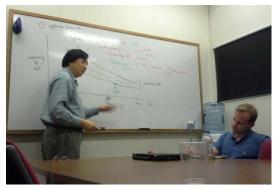












Phases — LFEEE (Lubricant Formulation to...)

Phase 1:

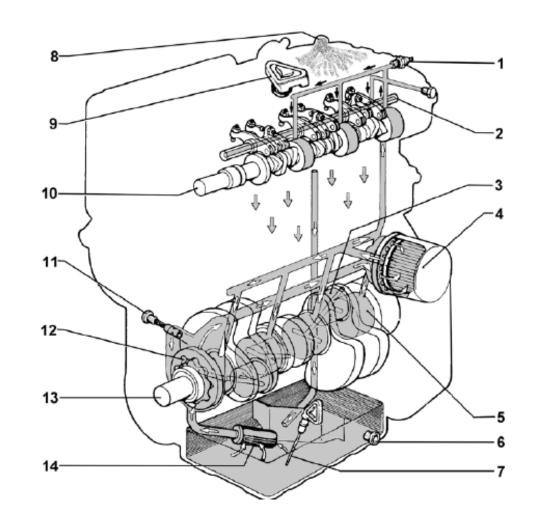
Investigate ideal formulations tailored to each major subsystem for best performance

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

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Project Start Date: Oct 1, 2011 Massachusetts Institute of Technology

Proposed Project Completion: Sep 30, 2014

Milestones M1, M2, M3.... on Chart indicate time schedule of completion of accomplishment

MAJOR TASKS/ 플 후 호 MILESTONES			SCHEDULE				
No.	MILESTONES	CY 2011	CY 2012	CY 2013	CY 2014		
		ONDJ	F M A M J J A S O N D	J F M A M J J A S O N D			
1.0 2.0 2.1 2.2 3.0 4.0 5.0	Develop Project Management and Planning Model Lubricant Effects on Individual Sub-Systems - For piston, ring, liner sub-system - For valvetrain sub-system Develop Lube Test Parameters w/ Industry Partners Perform Parametric Experiments on Lube Effects Data Analysis, Interpretation and Design Iterations MILESTONE 1 (M1) : Modeling Power Cylinder MILESTONE 2 (M2): Modelig Valvetrain MILESTONE 3 (M3): Develop Candidate Matrix MILESTONE 4 (M4): Modify/Prepare Test Engine MILESTONE 5 (M5): Instrument Diagnostics		M1 M3 M4 M5	M2	JBMAM	JJAS	
	MILESTONE / (M/): Tests with Floating Liner En	gine		M/			
6.0 7.0 7.1 7.2 7.3 8.0	Model Lube Formulations with Regional Variations Test, Optimize Composite Oil Formulations For Segregated Fower-cylinder, Valvetrain Subsystems For One-Oil Fully Mixed Combined System (Baseline) For Regional (Local) Modulation of Lubricant Properties Develop Practical Means to Implement New Formula MILESTONE 8 (M8): Model Variable Lube Formul MILESTONE 9 (M9): Parametric Lube Tests, one MILESTONE 10 (M10): Parametric Lube Tests, or	ations oil, full mixin ne oil, segreq	jated	M8 M9 M10	■ M11		
9 10 ases: T	Demonstrate Final Lube Formulation in Full System Evaluate & Test Impact on Aftertreatment Systems MILESTONE 12 (M12): Full Demonstration, Optin MILESTONE 13 (M13): Aftertreatment Impact Ass Proughout project Review lube formulation iterations with industry			M13	≡ M13	M12 M13	
	2: Bes 6.0 7.0 7.1 7.2 7.3 8.0 3: Pro 9 10	1: Best Lube Formulations for Subsystem 1: Develop Project Management and Planning Model Lubricant Effects on Individual Sub-Systems 2: For piston, ring, liner sub-system 3: For valvetrain sub-system 3: Proof of Concept, Final Demonstration Substance Substance Substance Substance	MILESTONES CY 2011 1: Best Lube Formulations for Subsystem O N D J 1: Develop Project Management and Planning 2: Model Lubricant Effects on Individual Sub-Systems 2: 1 - For piston, ring, liner sub-system 3: Develop Project Management and Planning 2: 2 - For valvetrain sub-system 3: Develop Lube Test Parameters w/ Industry Partners 4: Perform Parametric Experiments on Lube Effects 5: Data Analysis, Interpretation and Design Iterations MILESTONE 1 (M1) : Modeling Power Cylinder MILESTONE 2 (M2): Modelig Valvetrain 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 2: Best Composite Formulations for Combined System 6: Model Lube Formulations with Regional Variations 7: Test, Optimize Composite Oil Formulations 7: For Segregated Power-cylinder, Valvetrain Subsystems 7: For One-Oil Fully Mixed Combined System (Baselne) 7: For Segregated Power-cylinder, Valvetrain Subsystems 8: Develop Practical Means to Implement New Formulations MILESTONE 8 (M8): Model Variable Lube Formulations MILESTONE 9 (M9): Parametric Lube Tests, one oil, full mixin MILESTONE 10 (M10): Parametric Lube Tests, one oil, full mixin MILESTONE 11 (M11): Parametric Lube Tests, one oil, segreg MILESTONE 11 (M11): Parametric Lube Tests, one oil, segreg MILESTONE 12 (M12): Full Demonstration 9 Demonstrate Final Lube Formulation in Full System MILESTONE 12 (M12): Full Demonstration, Optimized Oil MILESTONE 13 (M13): Aftertreatment Impact Assessment asses: Throughout project 11 Review lube formulation iterations with industry Periodic formal reviews & reports - Deliver annual reports	MAJOR TASKS/ MILESTONES	MAJOR TASKS/ MILESTONES MILESTONES CY 2011 CY 2012 CY 2013 1. Describe Formulations for Subsystem 1.0 Develop Project Management and Planning 2.0 Model Lubricant Effects on Individual Sub-Systems 2.1 - For piston, ring, liner sub-systems 3.0 Develop Lube Test Parameters w Industry Partners 4.0 Perform Parametric Experiments on Lube Effects 5.0 Data Analysis, Interpretation and Design Interations MILESTONE 1 (M1) : Modeling Power Cylinder MILESTONE 2 (M2): Modeling Valvetrain MILESTONE 3 (M3): Develop Candidate Matrix MILESTONE 4 (M3): Develop Candidate Matrix MILESTONE 5 (M5): Instrument Diagnostios MILESTONE 6 (M5): Instrument Diagnostios MILESTONE 7 (M7): Tests with Floating Liner Engine 2. Best Composite Formulations for Combined System 6.0 Model Lube Formulations with Regional Variations 7.0 Test, Optimize Composite OI Formulations MILESTONE 6 (M5): Model Variations 7.1 For Segnated Fower-Oyliner, Valvetian Buotystems MILESTONE 6 (M5): Model Variations MILESTONE 6 (M5): Model Variations MILESTONE 6 (M5): Model Variations MILESTONE 6 (M7): Tests with Floating Liner Engine 2. Best Composite Formulations with Regional Variations MILESTONE 1 (M10): Parametric Lube Tests, one oil, segregated MILESTONE 1 (M11): Parametric Lube Tests, one oil, segregated MILESTONE 1 (M11): Parametric Lube Tests, one oil, segregated MILESTONE 1 (M11): Parametric Lube Tests, one oil, segregated MILESTONE 1 (M12): Full Demonstration Demonstrate Final Lube Formulation in Full System Demonstrate Final Lube Formulation (Polymized Oil MILESTONE 1 (M12): Full Demonstration, Optimized Oil M12 Feroids formulation iterations with industry 12 Periodic formulation iterations with industry 13 Periodic formulation iterations with industry 14 Periodic formulation iterations with	MAJOR TASKS/ MILESTONES MILESTONE (MI) MAY SERVICE MANAGEMENT SITE OF VARIABLE MAY SITE OF VARIABLE MAY SITE OF	

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

automotive lubricant

Additives (20-30%)

Base Oil

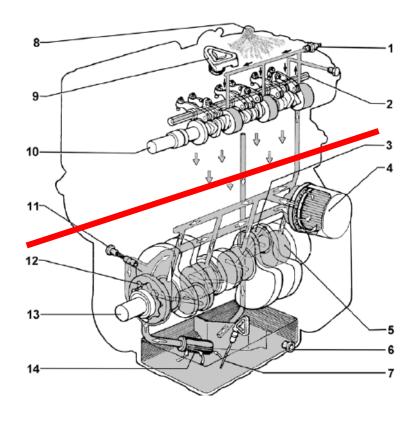
Background - Functional Requirements

Valvetrain

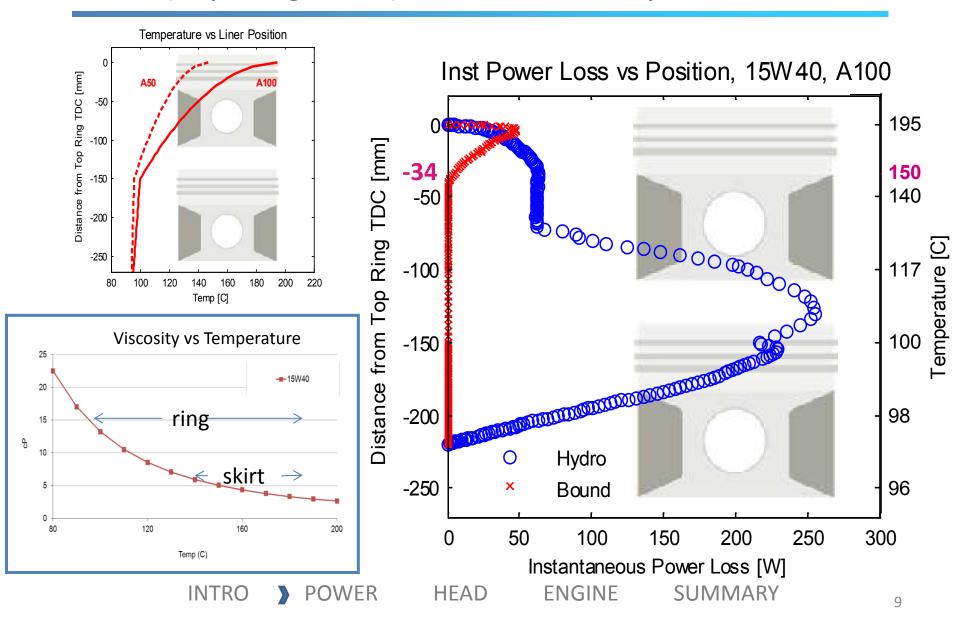
- High EHD pressures (~2000 MPa)
- Low Temp
- No combustion gas/soot
- No path to tailpipe

Power Cylinder

- Predominantly hydro
- High Temp (rings ~250C)
- Hostile (acidic) environment

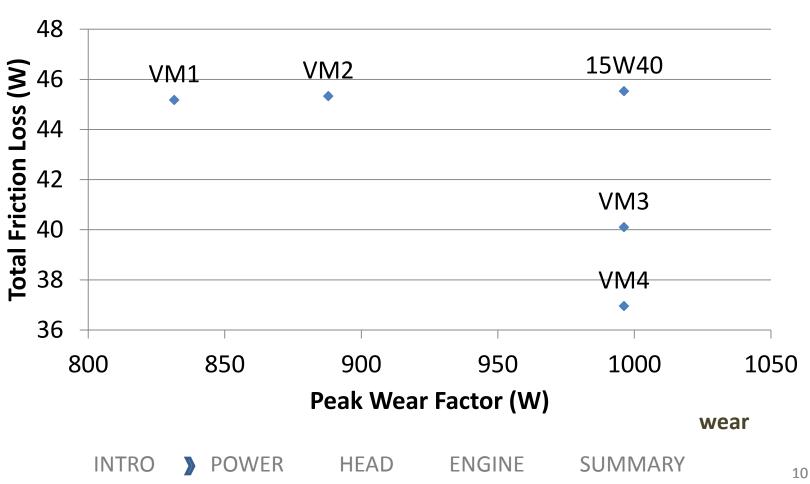


Friction (Top Ring, Skirt), Position & Temperature Domain

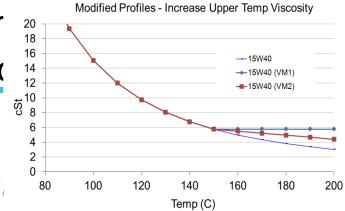


Optimizing –Upper and Lower Temperature Viscosity vs Friction and Wear

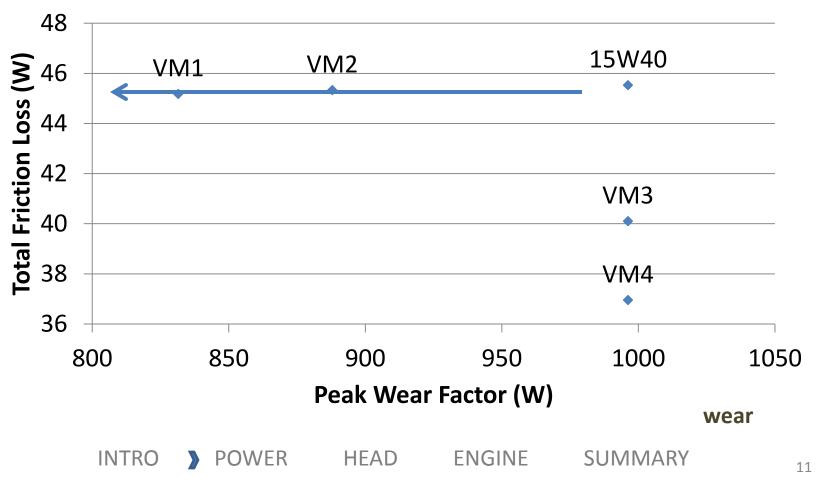
RING Peak Wear vs Friction Loss



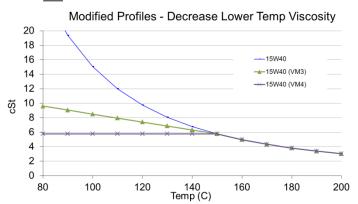
Optimizing –Upper and Lower Viscosity vs Friction and



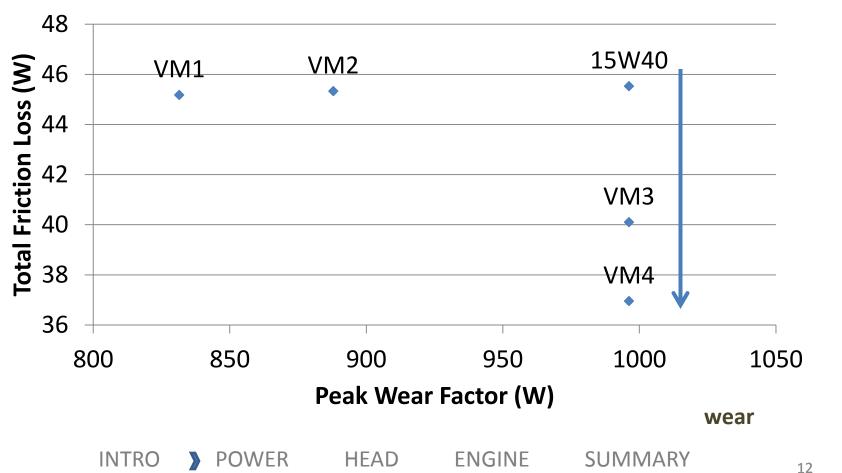
RING Peak Wear vs Fricti



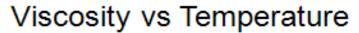
Optimizing –Upper and Low Viscosity vs Friction a

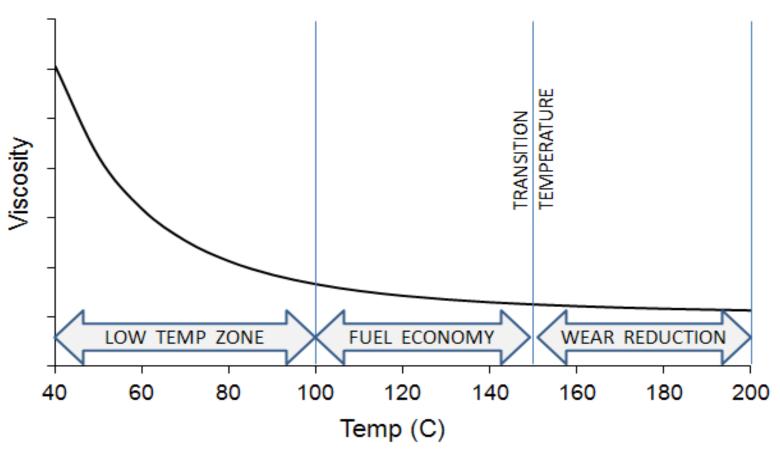


RING Peak Wear vs Fric

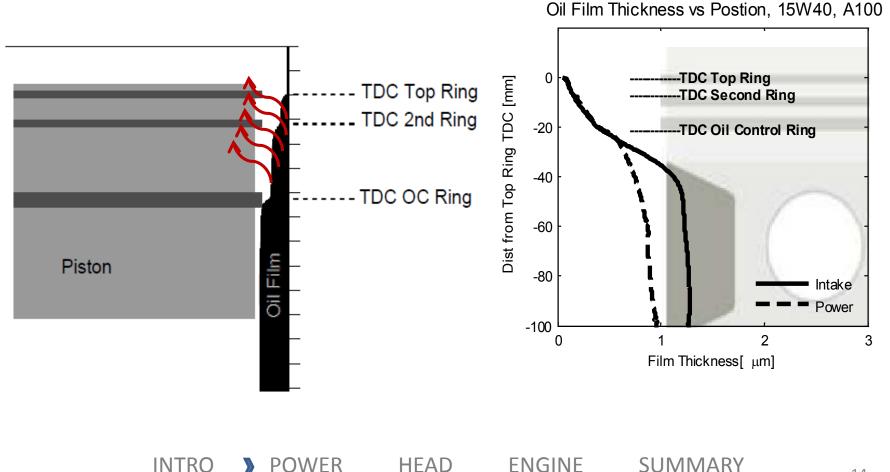


Viscosity vs Temp design parameters for η_{mech}

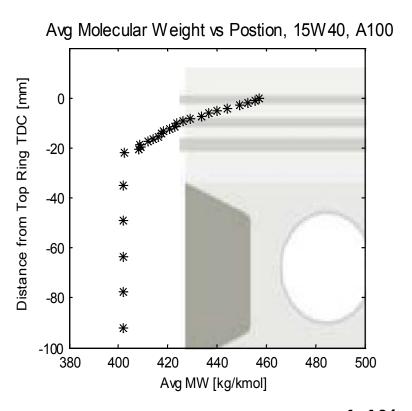


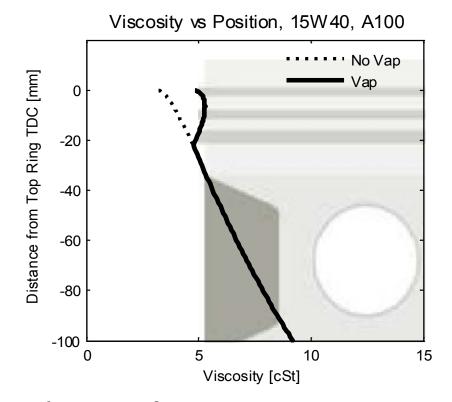


Vaporization/Friction Models



Vaporization/Friction Models





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

Power Cylinder modeling - Accomplishments/Looking Forward

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:

- Plumley, Wong, Molewyk, Park. "Optimizing Base Oil Viscosity Temperature Dependence For Power Cylinder Friction Reduction" SAE Paper 2014-01-1658
- Molewyk, Wong. "In Situ Control of Lubricant Properties for Reduction of Power Cylinder Losses through Thermal Barrier Coating" SAE Paper 2014-01-1659

Acknowledgements

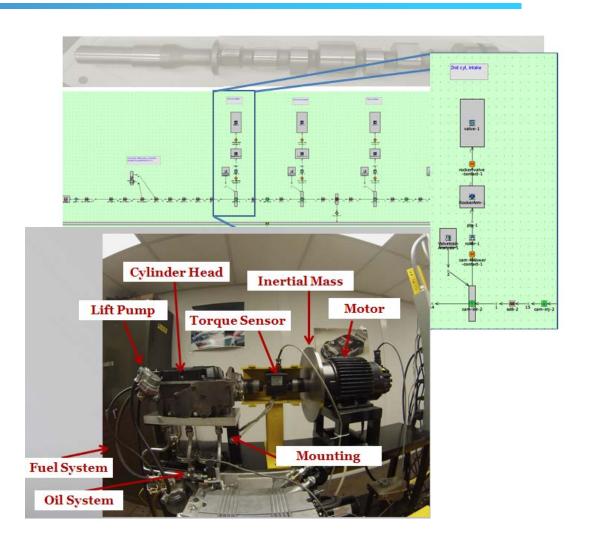
This work was supported by Cooperative Agreement DE-EE0005445 from the U.S Department of Energy. We gratefully thank our project sponsors, Dr Steve Przesmitzki and project monitor Nicholas D'Amico, for their support. We also appreciate the many helpful interactions with, and insights from, Dr Jai Bansal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

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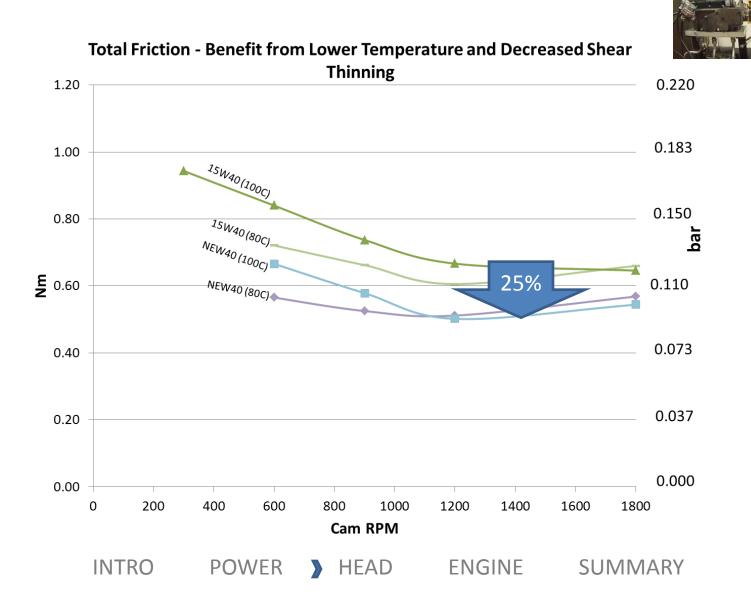


Valvetrain Temperature Dependence

- Valve Train modeled with GT Suite
- Experimental Bench Tests



Significant boundary friction identified at low speed in actual system



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
- Martins, Plumley, Wong. "Engine Lubricant Viscosity Optimization for Valvetrain and Power Cylinder Systems" STLE 2014 Annual Meeting





Split System Engine Tests

 Diagnostic tool 10-

HEAD

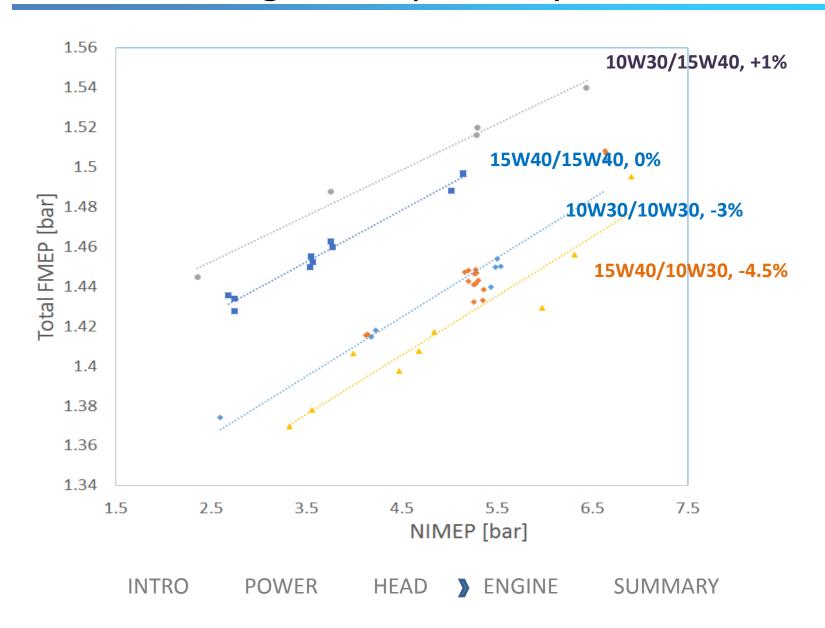
ENGINE

SUMMARY

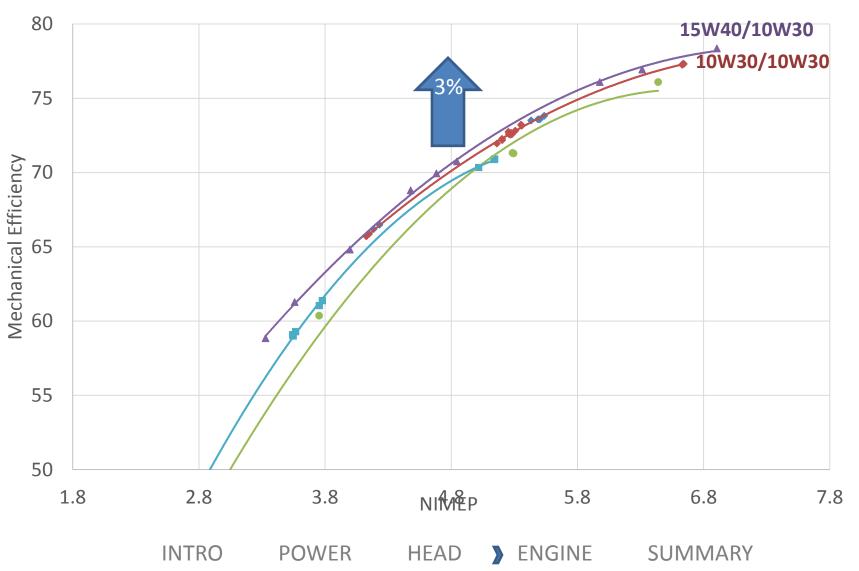
INTRO

POWER

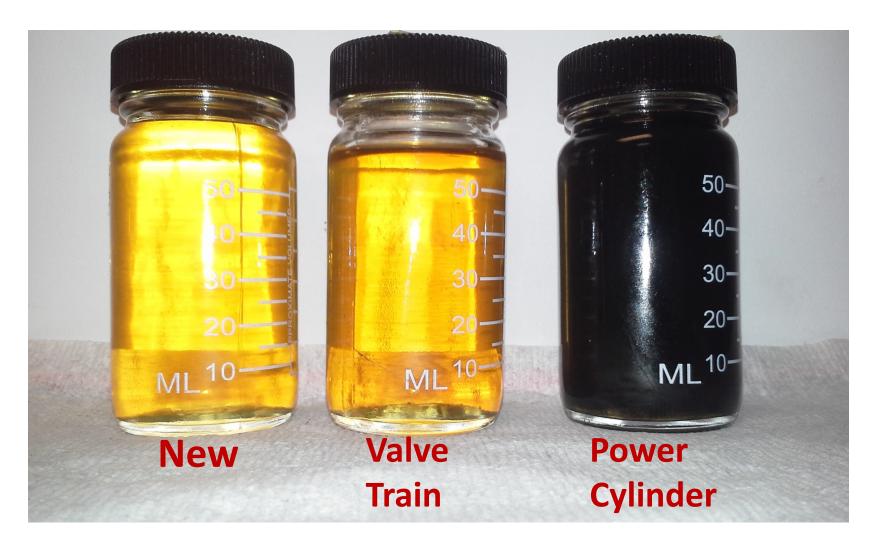
Slight total engine friction benefit with lower multigrade in power cylinder



Slight Total Mechanical Efficiency benefit with lower multigrade in power cylinder



Oil Aging - NEW40 sample, 8 hours in test engine



INTRO

POWER

HEAD

ENGINE

SUMMARY

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 shearthinning on engine friction using mineral and PAO base oils" STLE 2014 Annual Meeting
- Martins, Plumley, Wong. "Engine Lubricant
 Viscosity Optimization for Valvetrain and Power
 Cylinder Systems" STLE 2014 Annual Meeting

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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 1
- M5: Diagnostic instruments on test engine
- M6: Parametric Effects Tests 1
- M7: Floating liner test
 - = milestone reached

SUMMARY – Milestone Progress

- M8: Model local variable formulations
- M9: Parametric Tests, one oil, full mix 1
- 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)

INTRO POWER

HEAD

ENGINE

SUMMARY

CONCLUSIONS

- 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