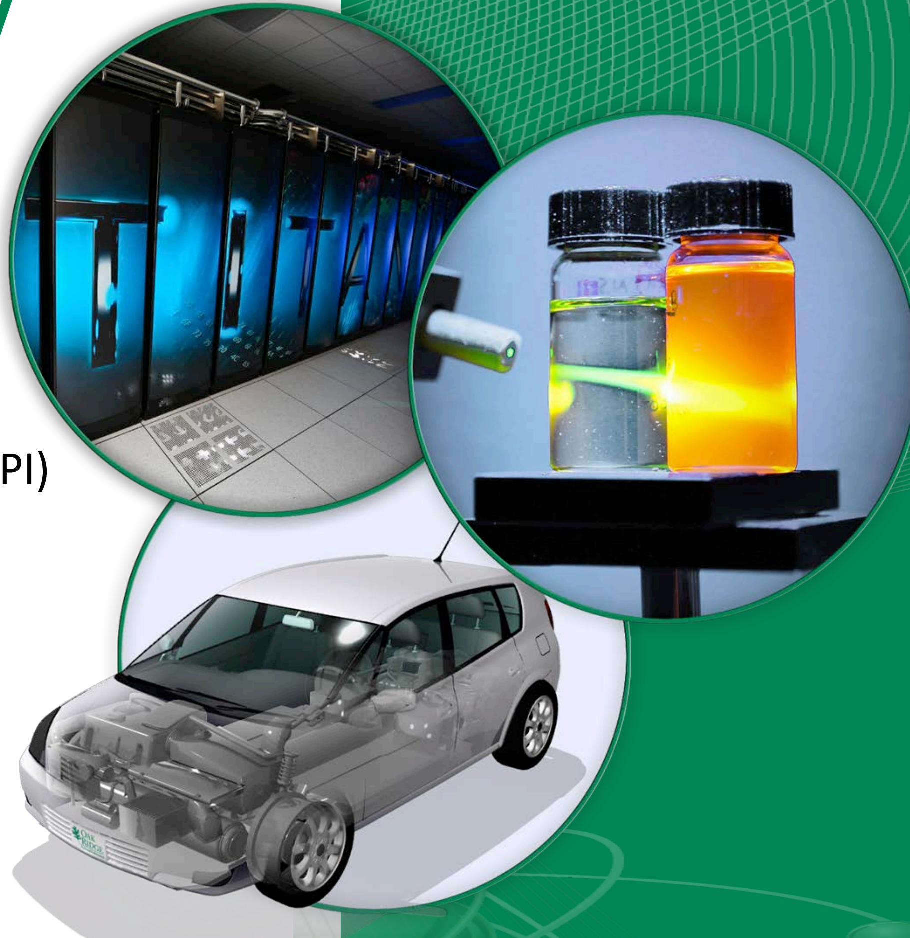
Lubricant Effects on Combustion, Emissions, and Efficiency



Presenter: Brian West

Melanie DeBusk, Shean Huff, Sam Lewis, Faustine Li, Eric Nafziger, Alex Pawlowski, Scott Sluder, Derek Splitter, John Storey, James Szybist, John Thomas, Robert Wagner (PI)

Oak Ridge National Laboratory

2016 DOE Annual Merit Review

Project ID # FT036

June 8, 2016

Technology Managers: Kevin Stork and Michael Weismiller

Fuels and Lubricants Technology

Vehicle Technologies Office

Oak Ridge National Laboratory

Project Overview

Timeline

- Effort is ongoing; re-focused annually to address DOE and industry needs
- FY13: Lubricants activity separated from "fuels and lubes"
  - Lubricant Additive Catalyst Effects, Lube Effects on GDI PM, Low-Speed Pre-Ignition, Vehicle-level Fuel Economy
- FY17: 4-lab team response to Labcall

Budget

- FY15: $750k
- FY16: $750k
- Covers 3 sub-projects

Barriers

- Inadequate data on long-term impact of fuel and lubricants on engines and emissions control systems.
  - MYPP 2.4 E

Partners

- Industry Collaborators
  - GM, Driven Racing Oil, Ford, Umicore
- National Laboratories
  - ANL, NREL, PNNL
- Academic
  - Univ. of Tennessee

Objectives and Relevance

Objectives

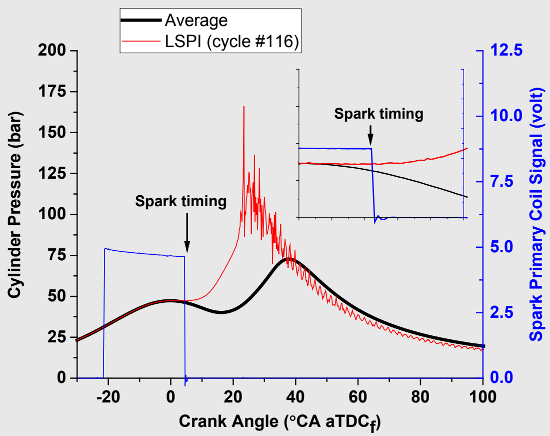
- Explore/understand cause(s) of Low-Speed Pre-ignition (LSPI)
- Elucidate lubricant property impacts on emissions and emissions control systems
  - Identify concerns associated with new lubricants
- Develop vehicle-based protocol to evaluate lubricants that can improve fuel economy

Relevance:

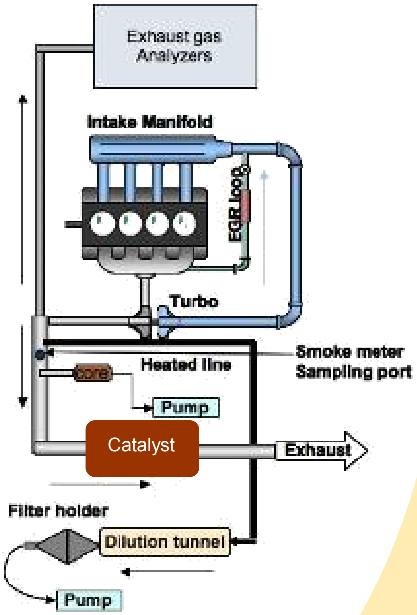
- Downspeeding and boosting are limited by LSPI
- Important to ensure new/novel lubricant or lubricant additives do not contribute to increased PM emissions or impact emissions control durability in a negative way
- Small fuel economy gain across legacy fleet can have significant impact on national fuel consumption

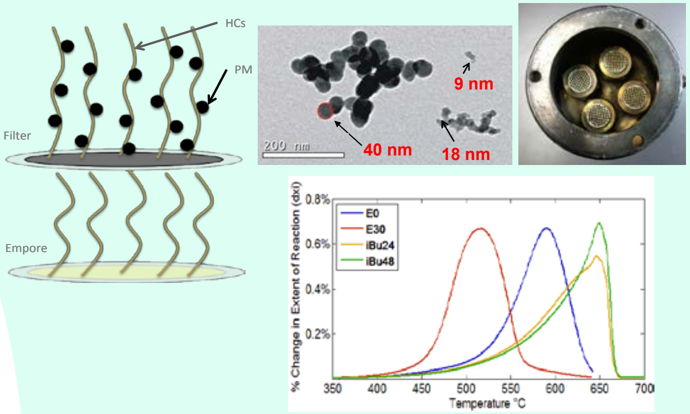
Approach

Bring together targeted, engine, vehicle, and flow-reactor studies with in-depth characterization of combustion, PM, HCs, emissions control devices, and fuel economy to better understand fuel and lubricant effects and interactions

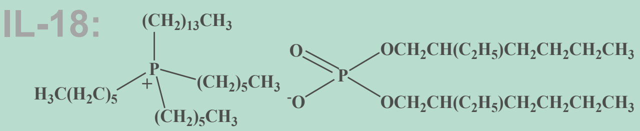


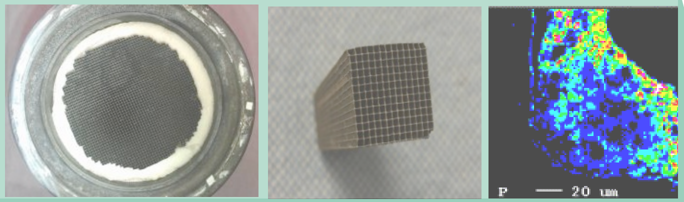
Exploring LSPI in engines





Fuel and lubricant effects on PM formation in DISI engines





Compatibility of advanced lubes with emissions control devices (FT014)

Vehicle-based fuel economy evaluation of advanced lubes

Milestones met or on track (✓=completed)

- **Low-Speed Pre-Ignition**
  - ✓ Successfully sampled/analyzed from Top Ring Zone in utility engine (FY15)
  - ✓ Completed setup of single-cylinder GDI engine (FY16)
  - – Report experimental results (FY16)
- **Lubricant and Fuel impacts on GDI particulate emissions**
  - ✓ Characterized PM morphology and lubricant contribution (FY14 and FY15)
  - – Commission GDI Engine Start Cart and collect cold start PM data (FY16)
- **Complete vehicle experiments to measure fuel economy differences between lubricants on multiple vehicles**
  - ✓ Cadillac SRX, DOHC V6 (same engine as Sequence VID test – FY14)
  - ✓ Chevrolet Silverado pushrod V8 (FY15-16)
    - ✓ FY15 – commercially available Lube
    - ✓ FY16 – PNNL Lube (FT035)
  - – Repeat on 4-cylinder engine (FY16)

Summary of Technical Accomplishments

- **Low-Speed Pre-Ignition Study**
  - Successfully sampled and analyzed liquid in top ring zone (TRZ) of running utility engine
    - Speciation of sample shows boiling point dependence – mostly larger aromatics
    - Increased load or decreased temperature increases TRZ liquid
  - Established dedicated single-cylinder GDI engine
    - Ford 1.6L EcoBoost (DRIVVEN controller)
    - Partner providing custom lubes for parametric variation of lubricants
- **Effects of Lubricants/Fuels on Emissions**
  - Quantified effects of lubricant additives on catalysts (FT014)
  - Examined lube and fuel impacts on GDI particulate emissions
    - Confirmed higher PM emissions for Start/Stop operation (Malibu GDI e-Assist)
    - No evidence of lubricant on PM collected on filters
    - Ethanol blend lowers, isobutanol increases PM mass and soot fraction
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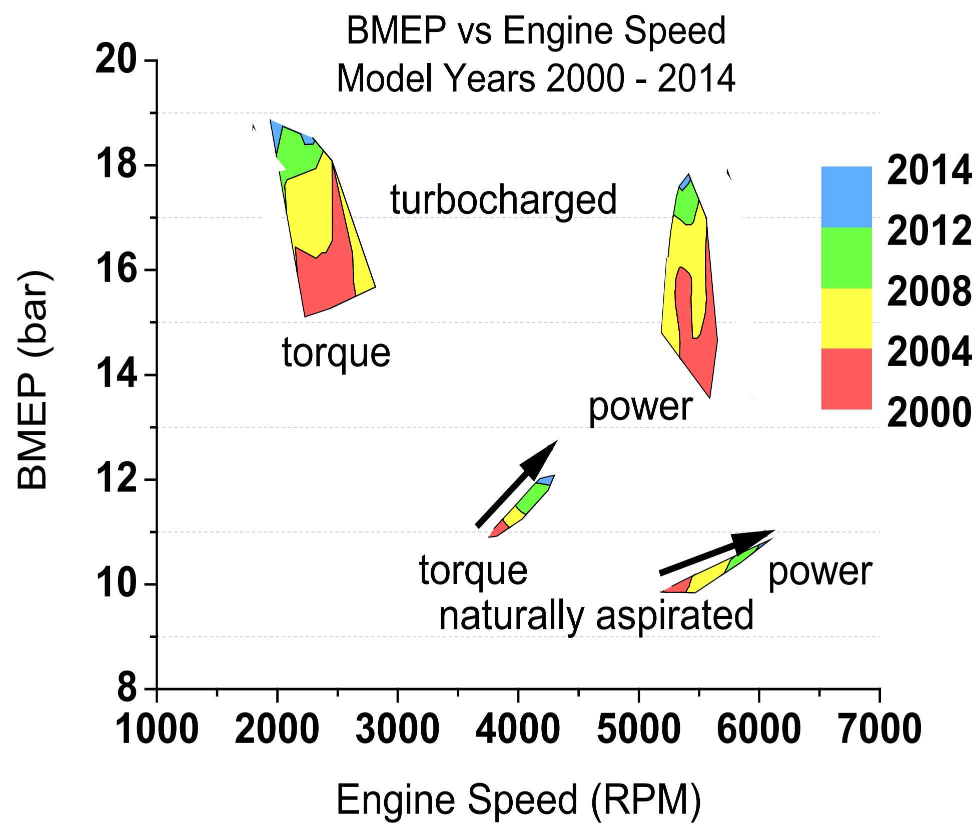
Downspeeding and Downsizing Trend is Increasing Conditions Conducive to LSPI

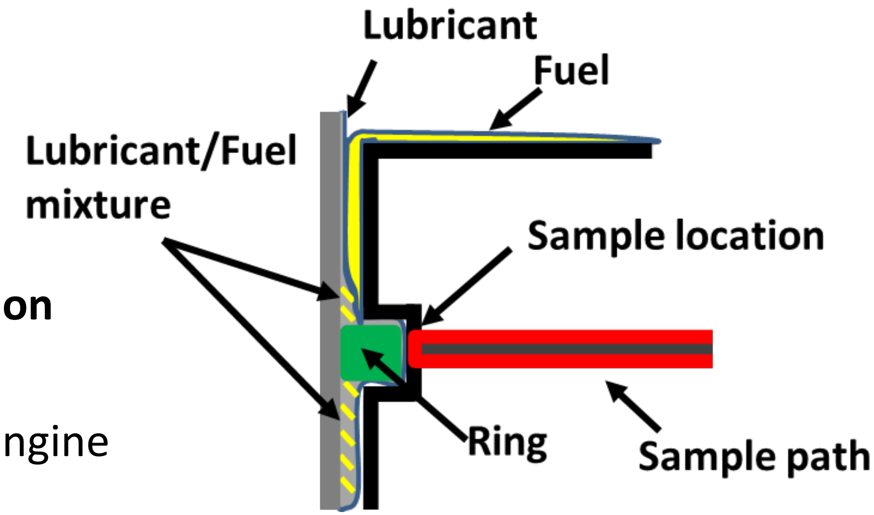
- **OEMs increasingly relying on downsped, downsized, turbocharged engines for Fuel Economy improvement**
- **Data mined from *Ward's* shows increase in rated power and BMEP for boosted engines since 2000**
  - **Increased use of >6 speed transmissions, CVTs lead to higher BMEP in real-world operation**
  - **Note: *rated* power and torque shown, not average over cycle**



[1] Pawlowski, Alexander, and Derek Splitter. *SI Engine Trends: A Historical Analysis with Future Projections*. No. 2015-01-0972. SAE Technical Paper, 2015.

Understanding the interactions of fuel and oil in LSPI are critical for realizing fuel economy potential of SI engines

Hypothesis: LSPI occurs from ignition source of liquid ejection from ringland area

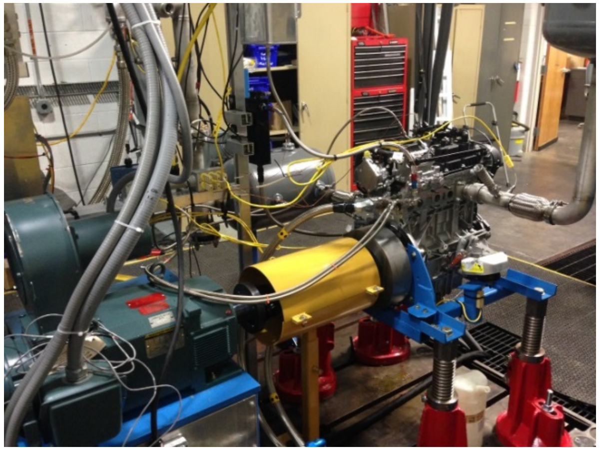


Proof-of-concept Experiment

- **In-situ top-ring zone (TRZ) sampling and speciation**
  - Air cooled utility-engine generator used
    - Direct liquid sampling from TRZ of running engine
    - GC/MS of sampled liquid employed

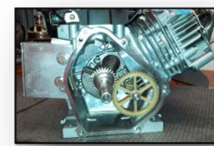
Setup of Modern Research Engine Experiment

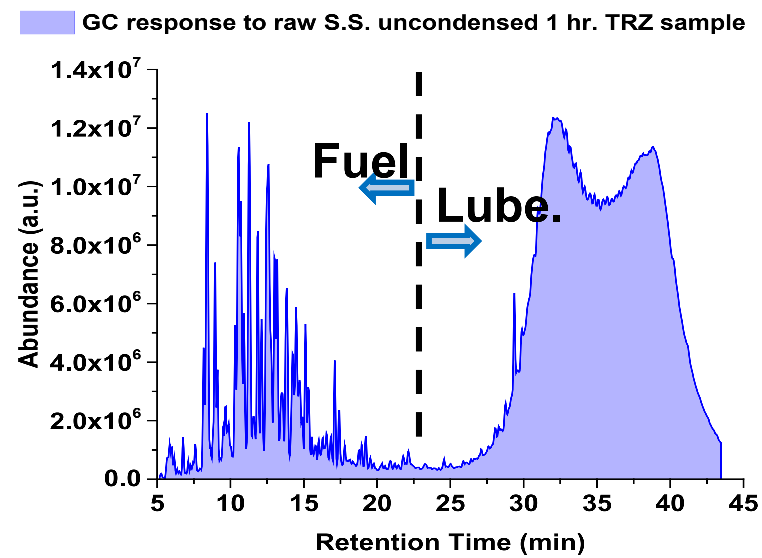
- **Dedicated LSPI single-cylinder engine**
  - Ford 1.6-L EcoBoost, converted to SCE



Completed sampling and analysis of liquid from Top Ring Zone (TRZ) on running utility engine

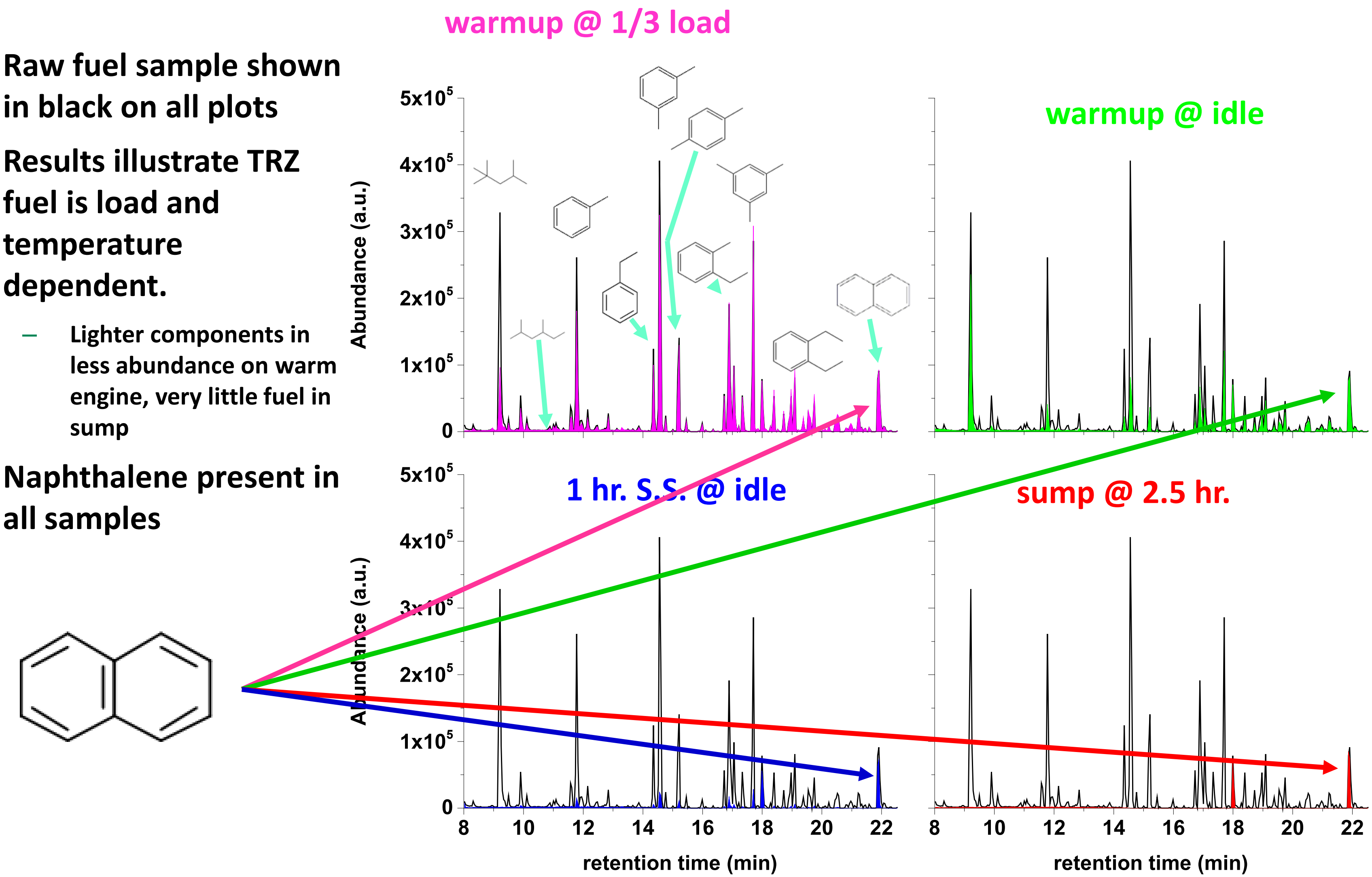
- Inexpensive development tool, proof of concept
  - Air-cooled, carbureted generator NOT representative of modern GDI engines
- Samples from TRZ collected during operation under multiple conditions
- Gas chromatography/mass-spectrometry (GC/MS) applied to raw fuel, raw lube, TRZ samples
- Results show significant fuel (23%) in TRZ liquid after 1 hour operation
- Results complementary to literature; Samples show change in TRZ fuel fraction with change in operating conditions
  - Fuel fraction of TRZ liquid highest for low coolant temperature and increased load
  - *Literature*: High load and low coolant temp leads to LSPI





Fuel retention in TRZ is condition and species dependent

- **Raw fuel sample shown in black on all plots**
- **Results illustrate TRZ fuel is load and temperature dependent.**
  - Lighter components in less abundance on warm engine, very little fuel in sump
- **Naphthalene present in all samples**



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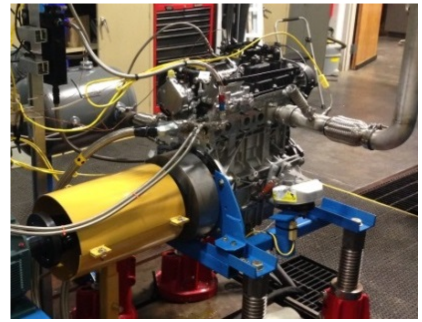
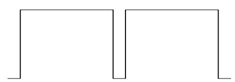
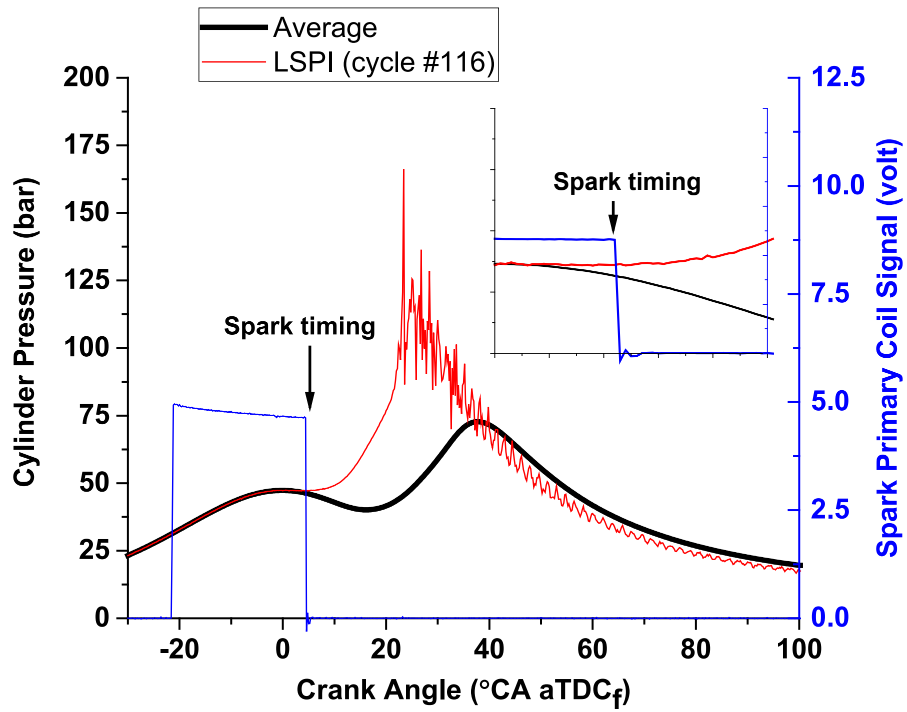
Single-cylinder Ford Ecoboost Set Up For Hi-Fidelity Measurements With Improved Control



- **Ford 1.6L EcoBoost converted to single-cylinder**
  - Simulated Turbocharging
  - Independent control of intake temperature and pressure, lube and coolant temperature, exhaust backpressure, etc.
- **Engine experiments conducted on automated cycle**
  - Alternate high/low load
  - Record ~15,000 consecutive combustion cycles per high load cycle

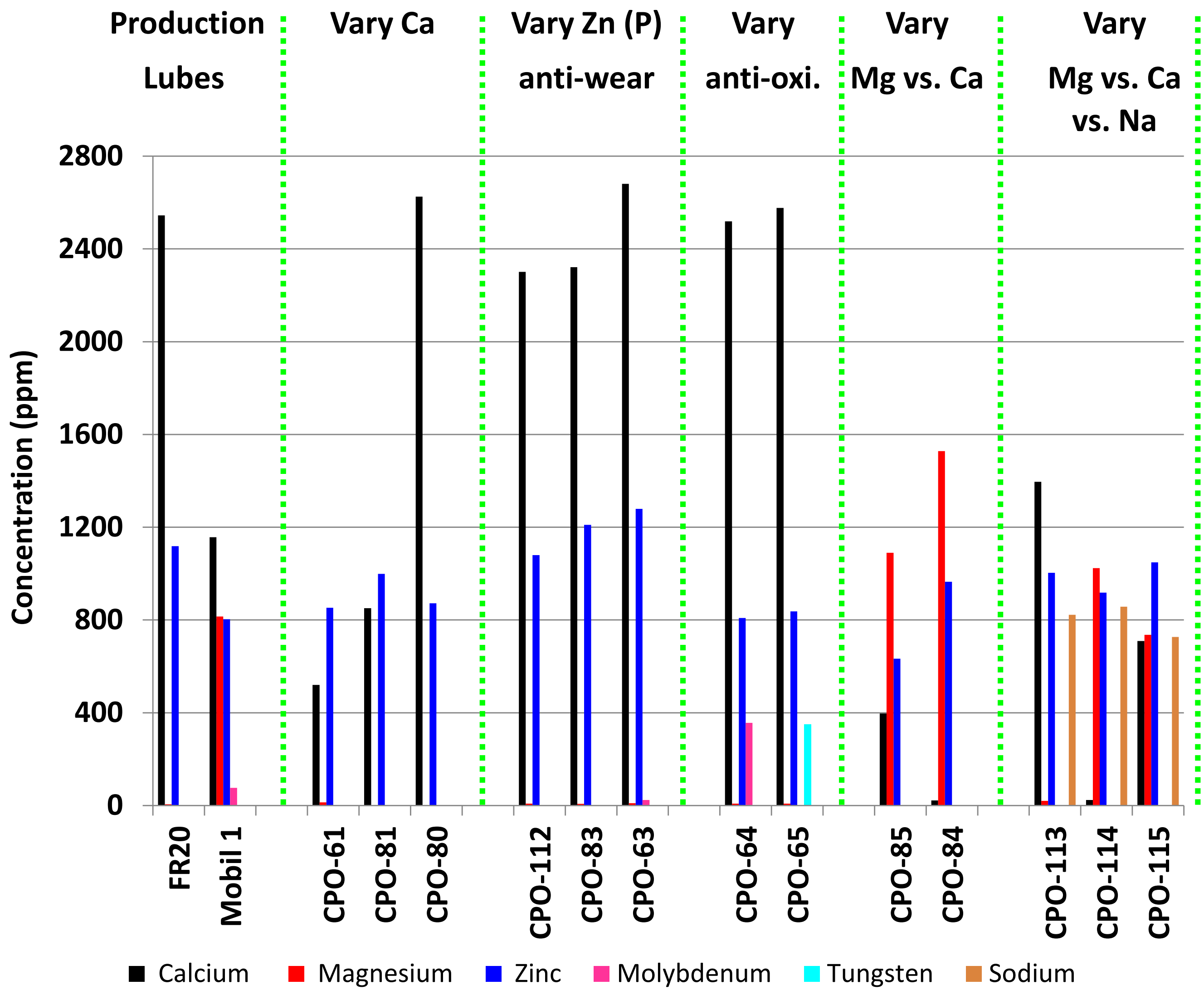


- **Engine failure "accomplishment"**
  - Hot spot runaway occurred at 26 bar IMEP, 2000 RPM
- **New engine operational**
  - Experiments underway
  - Exploring means to sample from TRZ



Established Partnerships for LSPI Experiments

- **Partnering with Driven Racing Oil – Providing custom lubes**
- **Parametric variation of lubricant properties in common basestock**
  - All lubes 5W-20, Group III (except Mobil 1)
  - Vary additive package in parametric manner
- **Leverage Co-Optima effort with fuel effects**
- **Partnering with NREL to measure ignition delay**
  - Same lubes, fresh and aged, evaluated in IQT



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Summary of Technical Accomplishments

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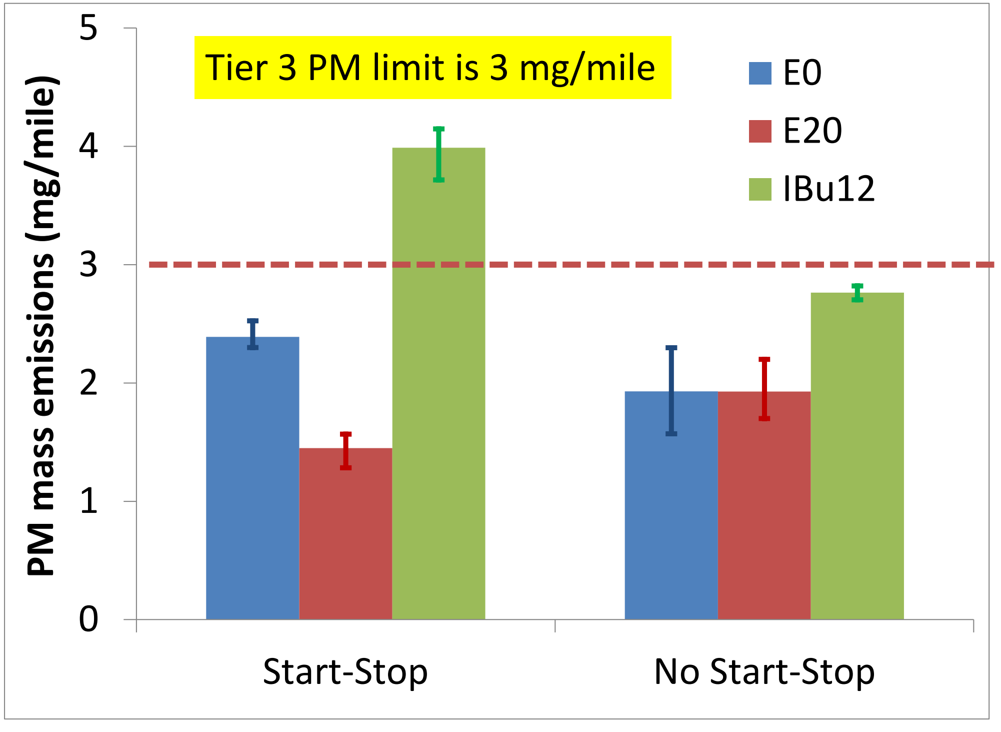
Effect of Start-Stop Operation on GDI Vehicle PM Emissions



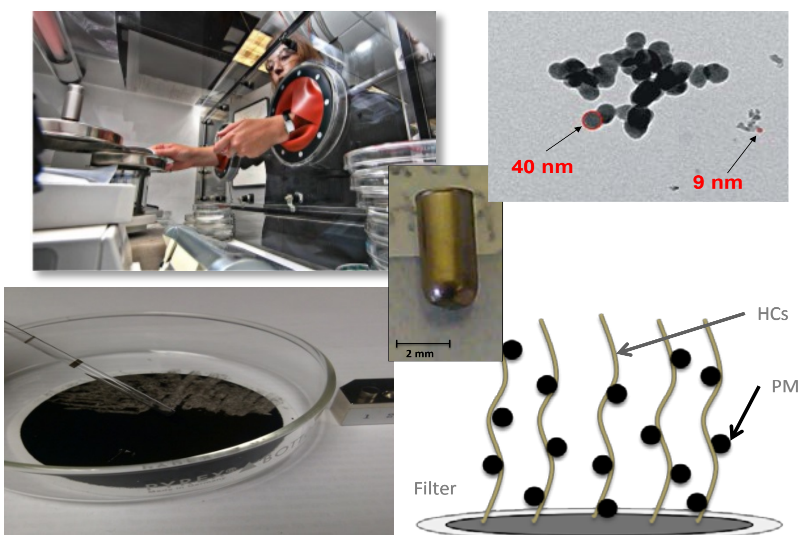
Will fuel saving technology of start-stop impact GDI PM emissions?
How do lube and fuel impact PM?

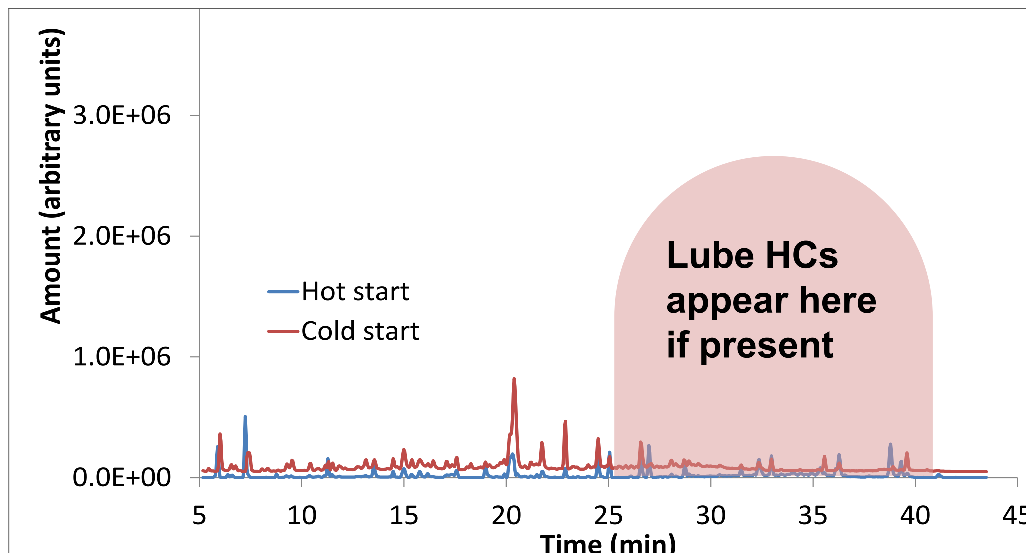
- Previously observed highest GDI PM during cold start of FTP
- Obtained and evaluated 2014 Malibu e-Assist vehicle (Fed. Tier 2 certification)
- Fuel chemistry may impact both fuel and lube contribution to PM
- Focus on Start-Stop effect on PM mass, soot and number
  - Tier 3 mass standard = 3 mg/mi
  - PM soot ≈ black carbon, a potent "greenhouse gas"
  - Particle number is currently regulated in Europe
    - Measured PN ~10-100 times Euro 6 limit*

*Test Vehicle certified to Federal Tier 2

Negligible Lubricant HCs Detected on PM sample filters

- **Thermal desorption/pyrolysis GC/MS method developed at ORNL to chemically characterize PM**
  - **HC fraction desorbed and analyzed by GC/MS**
  - **Heavier compounds such as lubricant HCs have longer retention time**
- **Three consecutive cold cycles on cold start filter, 27 consecutive cycles on hot start filter**
- **Soot emissions by photoacoustic sensor indicate majority of GDI PM is soot carbon**





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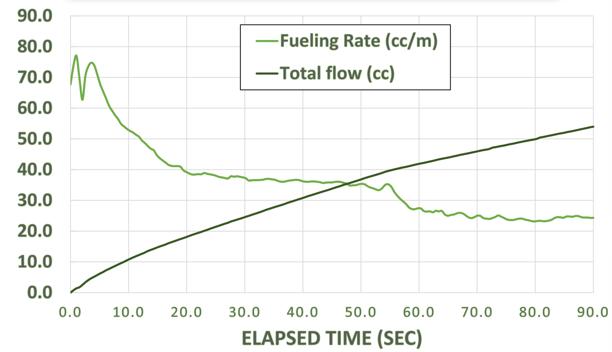
Established Mobile Start Cart Apparatus for Measuring Lubricant Effects on Emissions and Fuel Consumption

- Research tool to study cold start and hot re-start emissions and fuel consumption
- 2013 2.0-L Ford Focus ST engine
  - Modern turbocharged GDI
  - Dyno-ready ECU provided by Ford
- Mobile cart - Set up in Vehicle Laboratory for full-flow dilution emissions sampling
- Instrumented for cylinder pressure, crank angle, fuel flow, etc.
- Scheduled for investigating lubricant and fuel effects on GDI cold start particulate matter (PM)

Cold-start and idle fuel consumption



High accuracy fuel flow meter

High speed DAQ and control

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- **Vehicle Fuel Economy**
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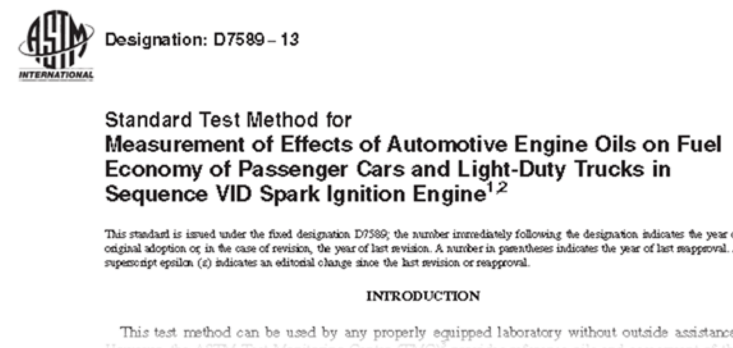
    - **Completed four campaigns (2 campaigns x 2 vehicles)**

"Energy Conserving" Lubricants are qualified on ASTM D7589 Sequence Test

- Lubricants compared to "ASTM Base Lube" (BL)
  - 20W-30 oil, provided to all Sequence test labs
  - GM V6 engine
- BSFC with test lubricant (TL) compared to BSFC with BL at six modal conditions after 16 and 100 hours of aging
  - Modal tests at relatively light load (backup slide)
  - Constant temperatures (115, 65, 35°C)
  - Weighted modes produce "Fuel Economy Improvement" (FEI) rating
  - Typical test result: "2.0% FEI" = FEI1 + FEI2
- ***No correlation to mpg, single engine result***



Designation: D7589 – 13

Standard Test Method for
Measurement of Effects of Automotive Engine Oils on Fuel Economy of Passenger Cars and Light-Duty Trucks in Sequence VID Spark Ignition Engine[1,2]

This standard is issued under the fixed designation D7589; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

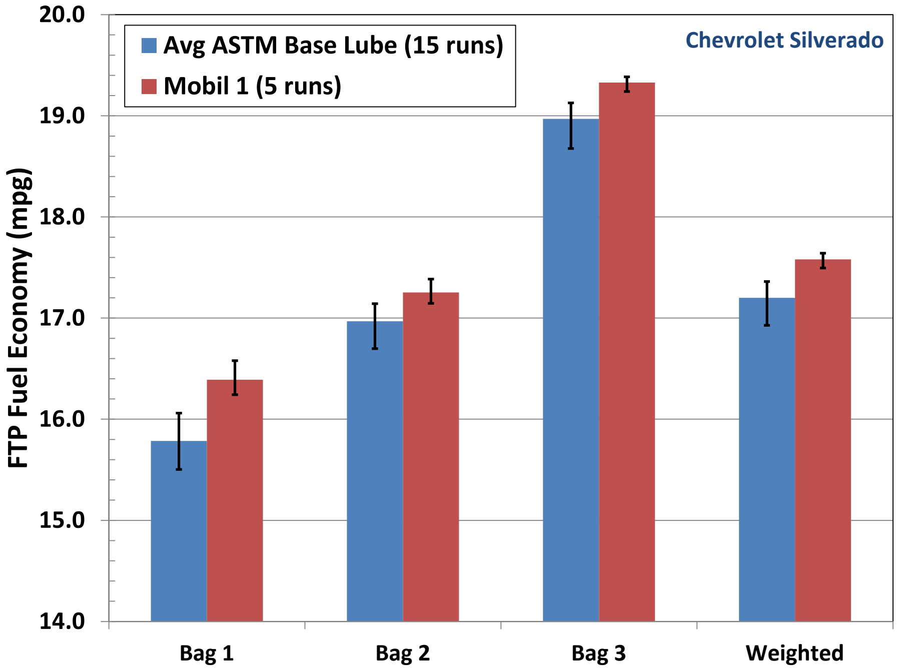
This test method can be used by any properly equipped laboratory without outside assistance.

Objective

- Develop vehicle-based test protocol to bridge Sequence Test results to "real-world" mpg
- Investigate lubricant impact on FEI in broader scope (e.g., 4, 6, 8 cylinder)

Fuel Economy Improvements from <1% to >3% Measured in Vehicle Experiments Compared to ASTM BL (backup slide)

- **Protocol includes City (FTP), Highway Fuel Economy Test (HFET), and Steady State Fuel Economy test (SSFE)**
  - **All Test Lubes anchored to ASTM Base Lube from Sequence VID/VIE (ASTM D7589)**
- **Completed 4 campaigns (2 veh x 2 campaigns)**
  - **Statistically significant FE improvement measured**
  - **Up next, vehicle with 4 cylinder engine**



Results show ability of careful vehicle FTP tests to distinguish fuel economy improvement of <1% to over 3%. Range bars show max and min of multiple tests. (similar results for HFET and SSFE)

Cadillac SRX has same DOHC V6 engine used in Sequence VID test

Experiment repeated in vehicle with pushrod V8 engine on 2 lubes (Mobil1 and PNNL prototype)

OAK RIDGE National Laboratory

2015 Review (FT007 – Fuel and Lubricant Effects on Emissions Control)

Emissions efforts reviewed last year as FT007. Score (3.3/4.0)

Reviewer Comments Favorable/Supportive:

- Good approach
- Multiple independent subprojects, broadens impact
- Milestones met in timely fashion
- Determining start-stop has no major impact on PM is addressing emissions barriers
- Interesting data on oxidative character of GDI PM
- Excellent collaboration
- Understanding fuel/lubricant interaction is complex, requires lots of effort
- Supports DOE goals
- Engine and flow-reactor studies with in-depth characterization of PM, HCs, and emissions control devices…successful

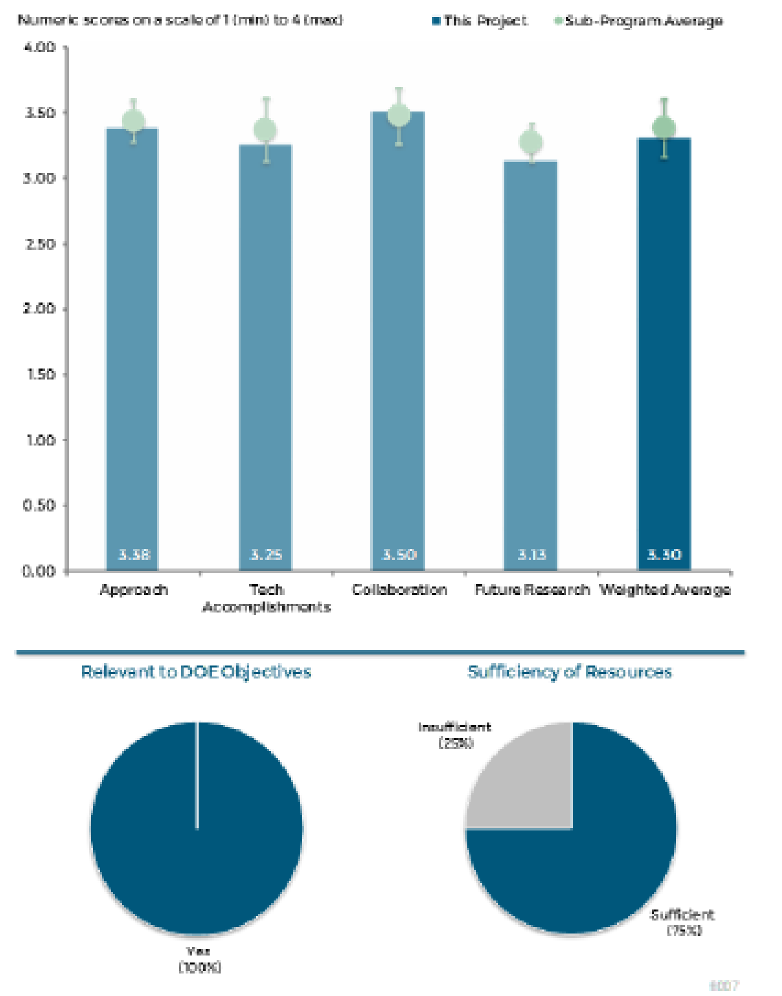


Figure 5-5 Fuel Effects on Emissions Control Technologies: Todd Toops (Oak Ridge National Laboratory) – Fuel and Lubricant Technologies

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Collaborators and Partners

- **Low Speed Pre-Ignition:**
  - Driven Racing Oils – custom lubricants
  - NREL – IQT applied to fresh and used oils
  - Informal support from major OEM
- **Fuel and lubricant formulation impacts on GDI particulate emissions:**
  - Umicore: gasoline particulate filter washcoating
  - Ford – engine controller for start cart
  - PNNL: PM collection and characterization campaigns
- **Lube Effects on Vehicle Fuel Economy**
  - PNNL – Prototype Lube evaluated
  - ASTM Test Monitoring Center – provide ASTM lubes
- **2017 Labcall partners**
  - ANL, PNNL, NREL
- Compatibility of emerging fuels and lubricants with emissions control devices (FT014):
  - NREL, Ford, Cummins, MECA
  - GM, Lubrizol, Shell: Ionic liquid development and evaluation

Remaining Challenges Future Directions

- **Low-Speed Pre-Ignition – Lube/fuel chemistry**

Understanding Lubricant/Fuel Interactions critical to ameliorating LSPI

Quantify LSPI tendency with matrix of custom-blended lubes

- **LSPI mechanics – wall impingement effects**

Does fuel impingement exacerbate LSPI?

Explore and quantify impingement effects with injector indexing

- **Effects of Lubricants on Fuel Economy**

Will small FE improvements be less detectable in downsped / downsized applications?

Evaluate additional engine types. Explore means to predict vehicle mpg change from Sequence test

- **Lubricant and fuel formulation impacts on GDI particulate emissions**

No direct contribution of lubricant to PM noted, but how do fuel switching or lubricant switching affect PM?

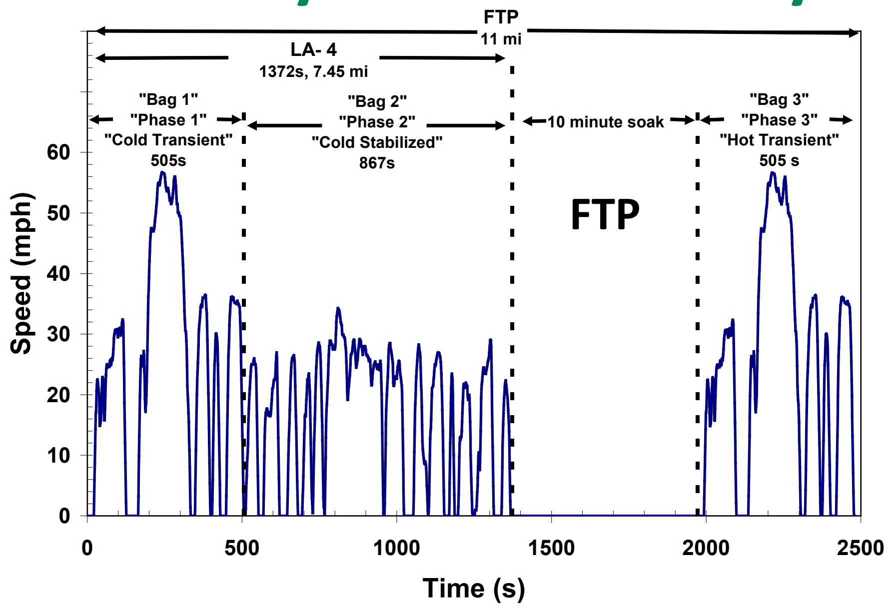
Examine PM from cold and hot starts with range of lubricants and fuels

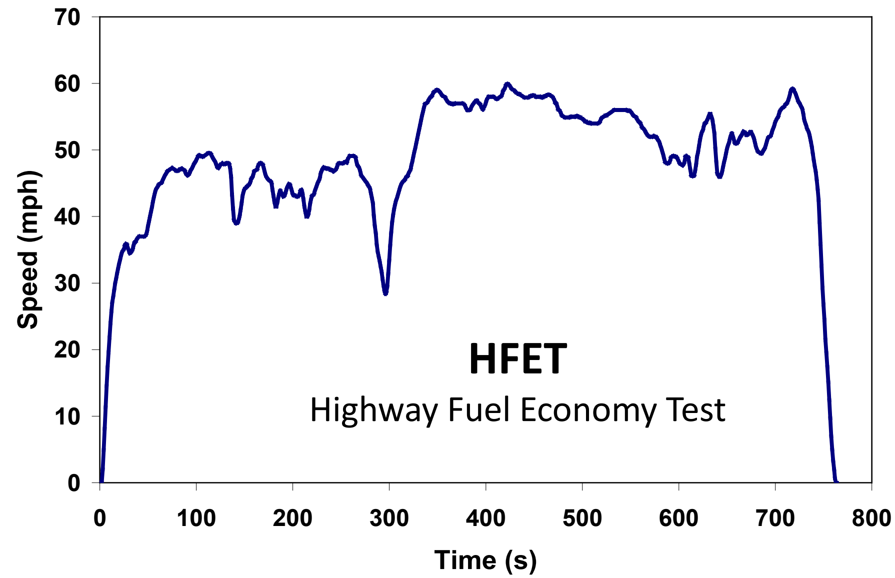
Summary

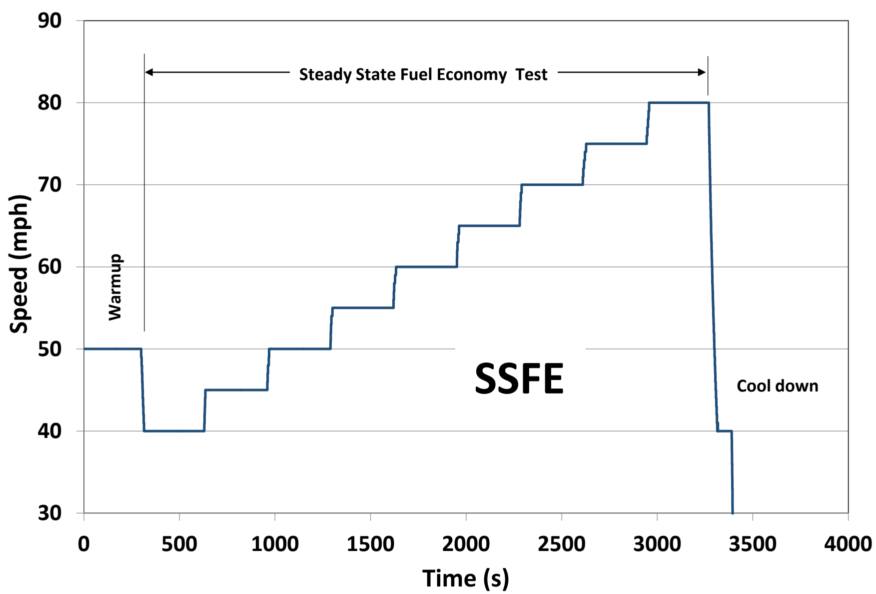
- Relevance: Studies provide understanding of impacts of lubricants on LSPI, PM emissions, and fuel economy.
- Approach: Targeted engine, vehicle, and flow-reactor studies with in-depth characterization of PM, HCs, and fuel economy to better understand lubricant effects and interactions.
- Collaborations: Wide-ranging collaboration with industry, academia, and other national labs designed to maximize impact and lead to marketable solutions
- Technical Accomplishments:
  - Developed and employed engine-based test stands to explore LSPI, emissions, and fuel economy impacts of lubricants
    - Speciation of top-ring zone liquid confirms boiling point dependence and effect of engine conditions
    - Established vehicle-based method to measure mpg improvement from lubricants
    - Quantification of fuel and lubricant impacts on GDI PM
- Future Work: well-designed plans in place to address remaining barriers; guidance from industry incorporated into future directions

TECHNICAL BACKUP SLIDES

Measuring Lubricant Effect on Vehicle Fuel Economy Currently Focused on 3 Cycles







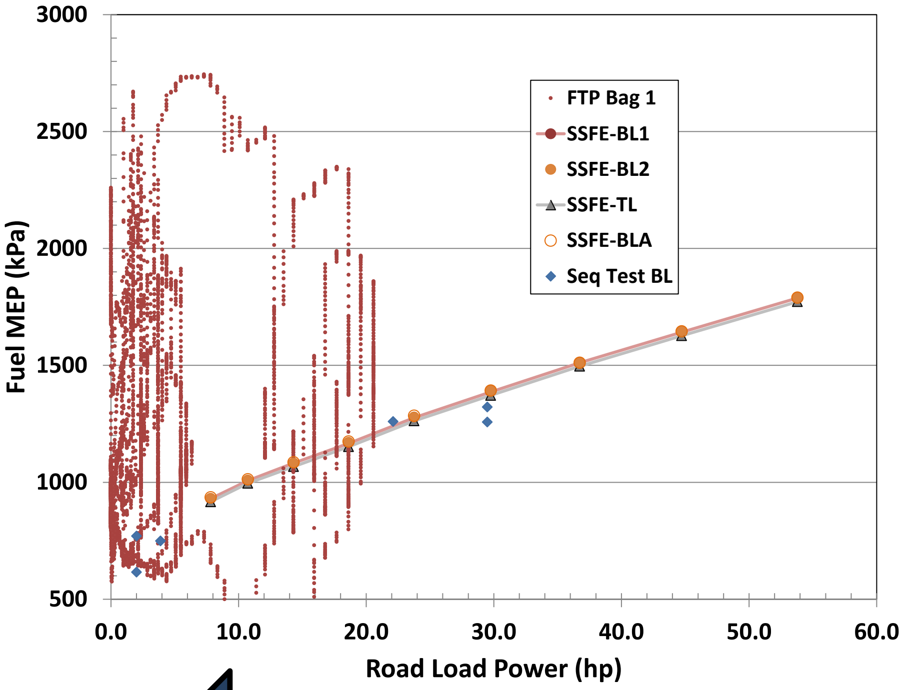
- **Federal Test Procedure (FTP), also known as City Cycle**
  - Includes “cold” start at 75°F
  - Used in emissions and fuel economy certification
- **HFET – Highway Fuel Economy Test**
  - Also for FE certification, warm engine
- **Steady State Fuel Economy Test**
  - Custom cycle, 5 min at each of 9 speeds

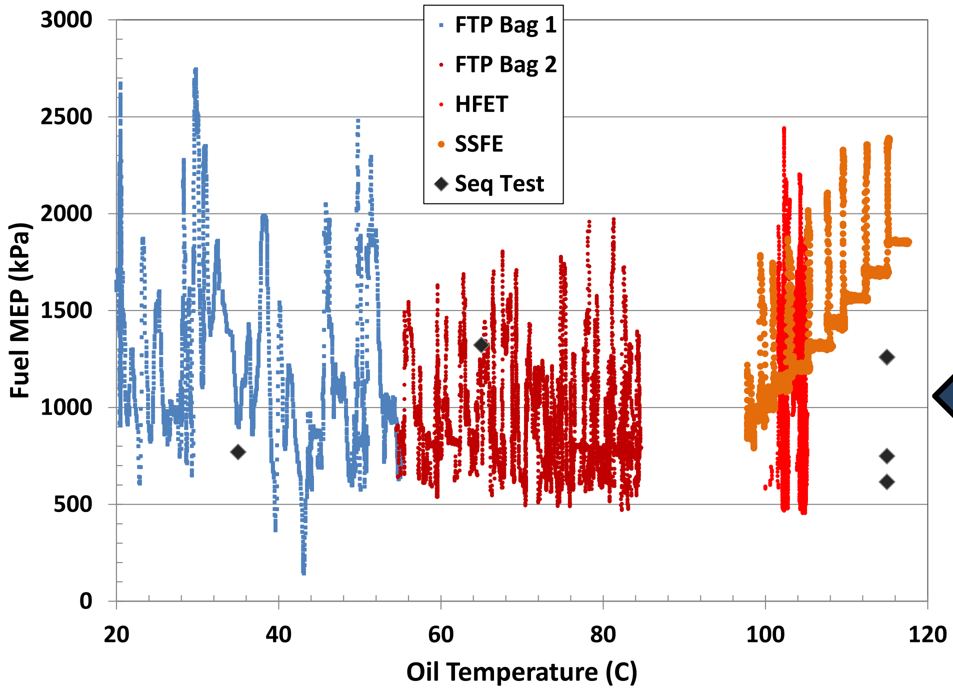
Bridging vehicle Fuel Economy tests to Sequence tests:

Fuel Mean Effective Pressure (Fuel MEP) normalizes to engine size and illustrates overlap of various tests.

$$\text{Fuel MEP} = \frac{\text{mass rate}_{fuel} * LHV*2}{Displacement*RPM}$$

- Six modes of Sequence test at fairly light loads
- Plot shows Fuel MEP vs hp for Seq Test, cold bag of FTP, SSFE





- Sequence test conducted at fixed oil temperatures
- Wide variation in oil temperature in transient vehicle operation
- FTP bag 1&2, HFET, SSFE, Seq Test Shown

Results: GDI vehicle PM depends on fuel and mode

- Lowest **Cold Start** PM mass, soot and number measured with **E20**
- **Hot start** PM affected differently:

Hot Start, Lowest values:	No Start-Stop	Start-Stop
PM Mass (Filter)	iBu12	E0
Soot Mass (AVL-MSS)	iBu12	E20
Particle # (EEPS)	iBu12	E0

- ORNL measured particle number emissions for FTP over order of magnitude higher than European reg (Test vehicle certified to Federal Tier 2)
  - (~10^{13} /mile vs. ~10^{12}/mile)

How about lubricant contribution?

- Not conclusive, no lubricant found in PM organic fraction by GC-MS
- Future Start-Cart studies will isolate start-up, lube impact on PM

Why is this research important?

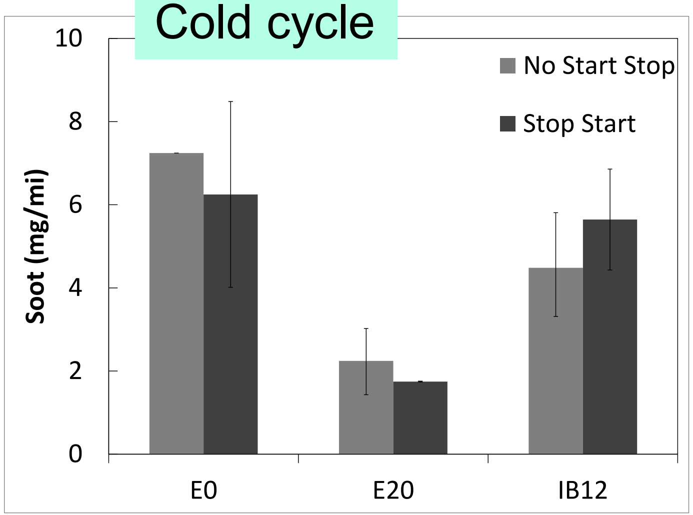
- Lower lubricant viscosity can lead to more volatility in combustion chamber
- Start-up has highest PM emissions for GDI
- Start-stop will impact particulate filter operation if GPF needed in 2025

Takeaway: Operation and fuel both have to be considered for PM control strategies

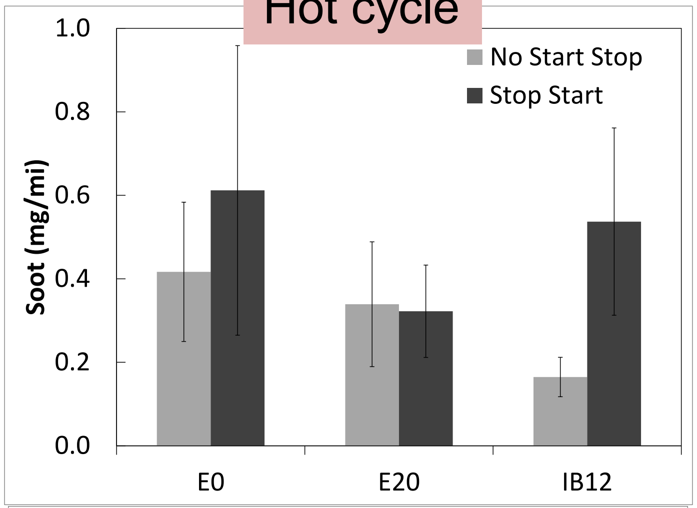
Start-stop mode + fuel influence soot, PN production for hot drive cycle

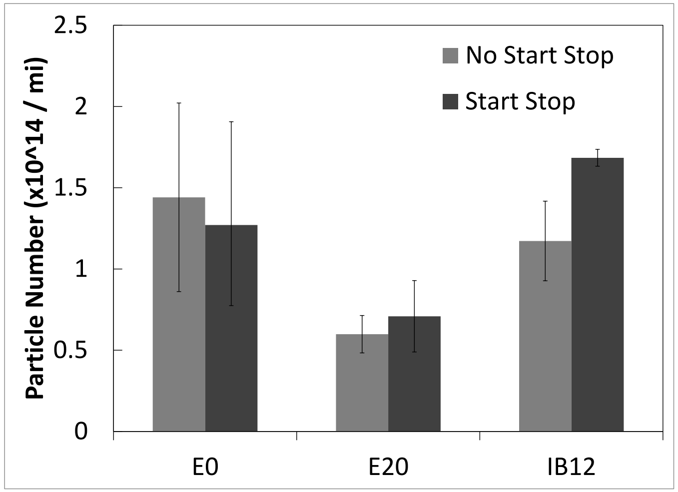
- Soot measured with photoacoustic sensor (AVL), 10X higher for cold cycle
- Particle number measured with differential mobility analyzer (EEPS), 5x higher for cold cycle
- E20 has a larger effect over cold cycles; IB12 has larger effect for hot cycle
- Test vehicle: 2014 Chevrolet Malibu, Federal Tier 2

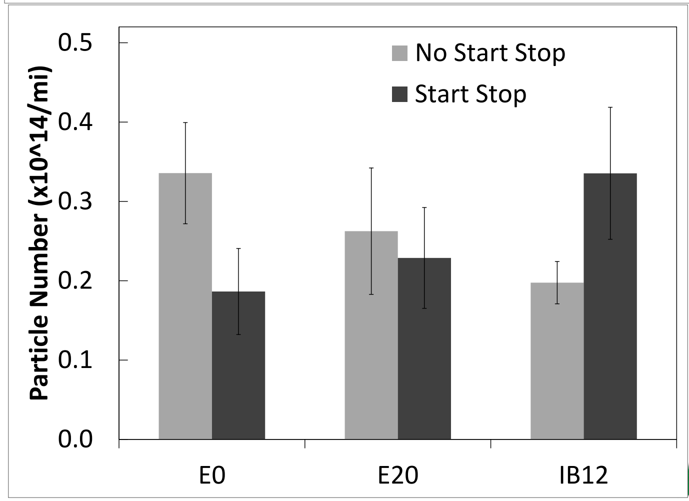
Cold cycle



Hot cycle







ANOVA (Analysis Of Variance) for GDI PM Data* shows interactions between fuel and start-stop mode

Soot	F	p
Fuel (E0, E20, IB12)	5.19	0.0072
Mode (SS, no SS)	19.18	0
Fuel * Mode	14.54	0

Particle Number	F	p
Fuel (E0, E20, IB12)	1.31	0.273
Mode (SS, no SS)	1.78	0.1837
Fuel * Mode	56.86	0

- **E0= 87 AKI gasoline;**
- **E20 =20% ethanol in the E0;**
- **IB12 = 12% isobutanol in the E0**
- **SS= start-stop *enabled***
- **No SS = start-stop *disabled***
- **Null hypothesis: there is no difference between fuels or start-stop modes for PM generation**
  - **$p < 0.05$ means null hypothesis is rejected**
  - **$p < 0.05$ is statistically significant**
- **For soot PM production, Fuel, Mode, and their interaction produced a significant difference in soot emissions**
- **For particle number, Fuel and Mode did not produce a significant effect, but their interaction does affect PN**

*Test Vehicle: 2014 Federal Tier 2