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Ethanol Optimized Engine

Ford Motor Company
AVL Powertrain Engineering, Inc.
Ethanol Boosting Systems LLC

USDA Biofuel Seminar Series
March 29, 2011

Ethanol Optimized Engine

Public domain sources used for the slides in this presentation:

DOE merit reviews and annual reports

SAE 2009-01-1490, "Optimal Use of E85 in a Turbocharged Direct Injection Engine”

SAE 2010-01-0585, “Development of the Combustion System for a Flexible Fuel Turbocharged Direct Injection Engine”

Paper not referenced in this presentation, but written based on work performed during the course of the project:

SAE 2011-01-0337, “Blowdown Interference on a V8 Twin-Turbocharged Engine”

Presentation Outline

- Project overview and objectives
- Background
  - Charge cooling with direct injection of ethanol
  - Dual fuel (E85 DI + gasoline PFI) concept and leveraging
- E85 optimized engine initial targets and approach
- Optical engine and single cylinder engine development
- Multi-cylinder engine development
- Comparison to baseline gasoline engine
- Summary

Project Overview

- Joint project with Ford (project lead), AVL, and EBS to design and develop an ethanol optimized engine including dual fuel capability for the F-Series pickup.

- Timeline
  - Project start date – Oct 2007
  - Project end date – Dec 2011

Initial Project Objectives

- Develop a roadmap to demonstrate a minimized fuel economy penalty for a F-series FFV pickup truck with a highly boosted, high compression ratio spark ignition engine optimized to run with ethanol fuel blends up to E85.
- Develop and assess a dual fuel concept for on-demand direct injection of E85.
- Reduce FTP 75 energy consumption by 15% - 20% compared to an equally powered vehicle with a current production gasoline engine.
- Meet ULEV emissions, with a stretch target of ULEV II / Tier II Bin 5.

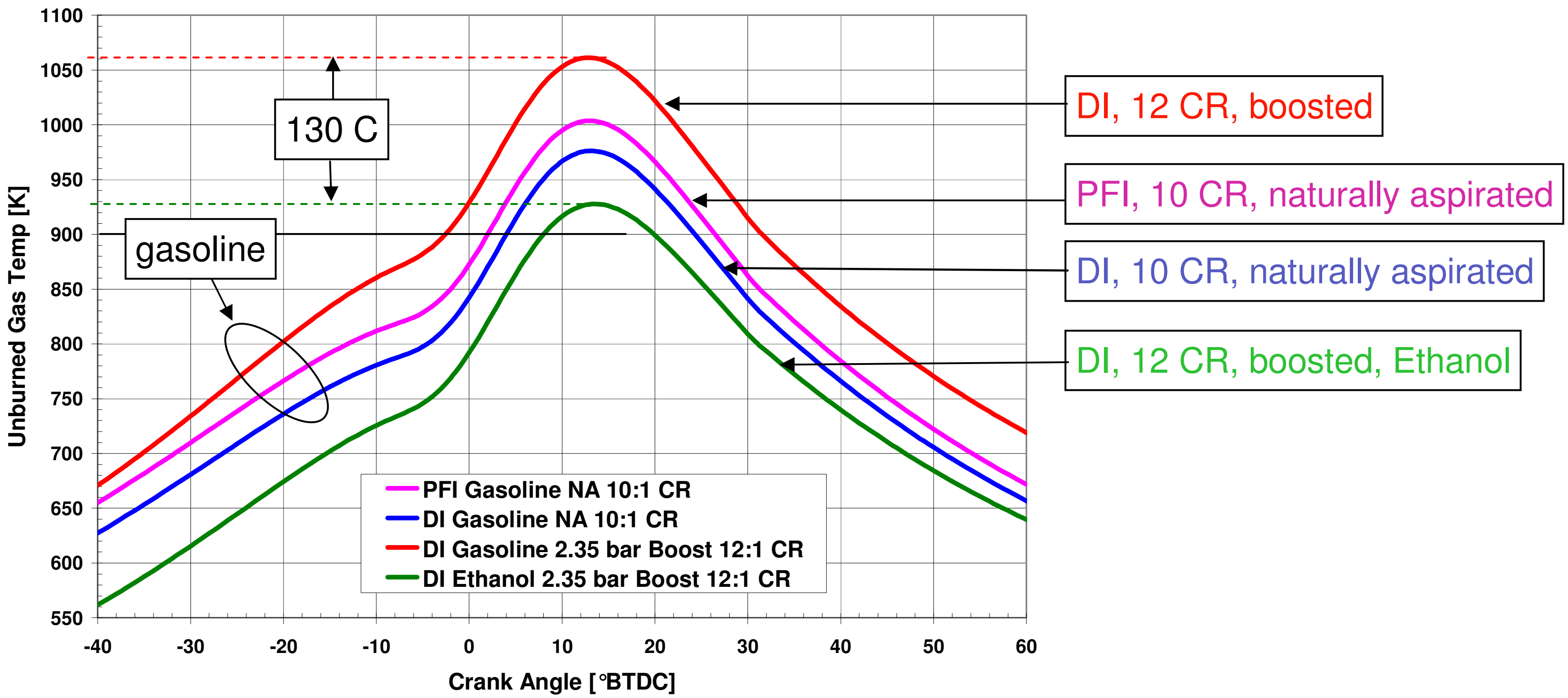
Background - Ethanol Properties

	E100	Gasoline
Octane (RON)	108	91 - 98
Heat of vaporization (kJ/kg)	840	~ 350
NHV (MJ/kg)	26.9	~ 43.5
Stoichiometric A/F	9.0	~ 14.6
NHV of stoich fuel quantity[1]	1.0 x base	base
Heat of vaporization at stoich[1]	3.9 x base	base
Density (kg/L)	0.785	~ 0.745
NHV volumetric basis (MJ/L)	0.65 x base	base
CO_2 emissions (gCO_2/MJ)	.97 x base	base
CO_2 emissions (gCO_2/L)	.64 x base	base

[1]per quantity of air

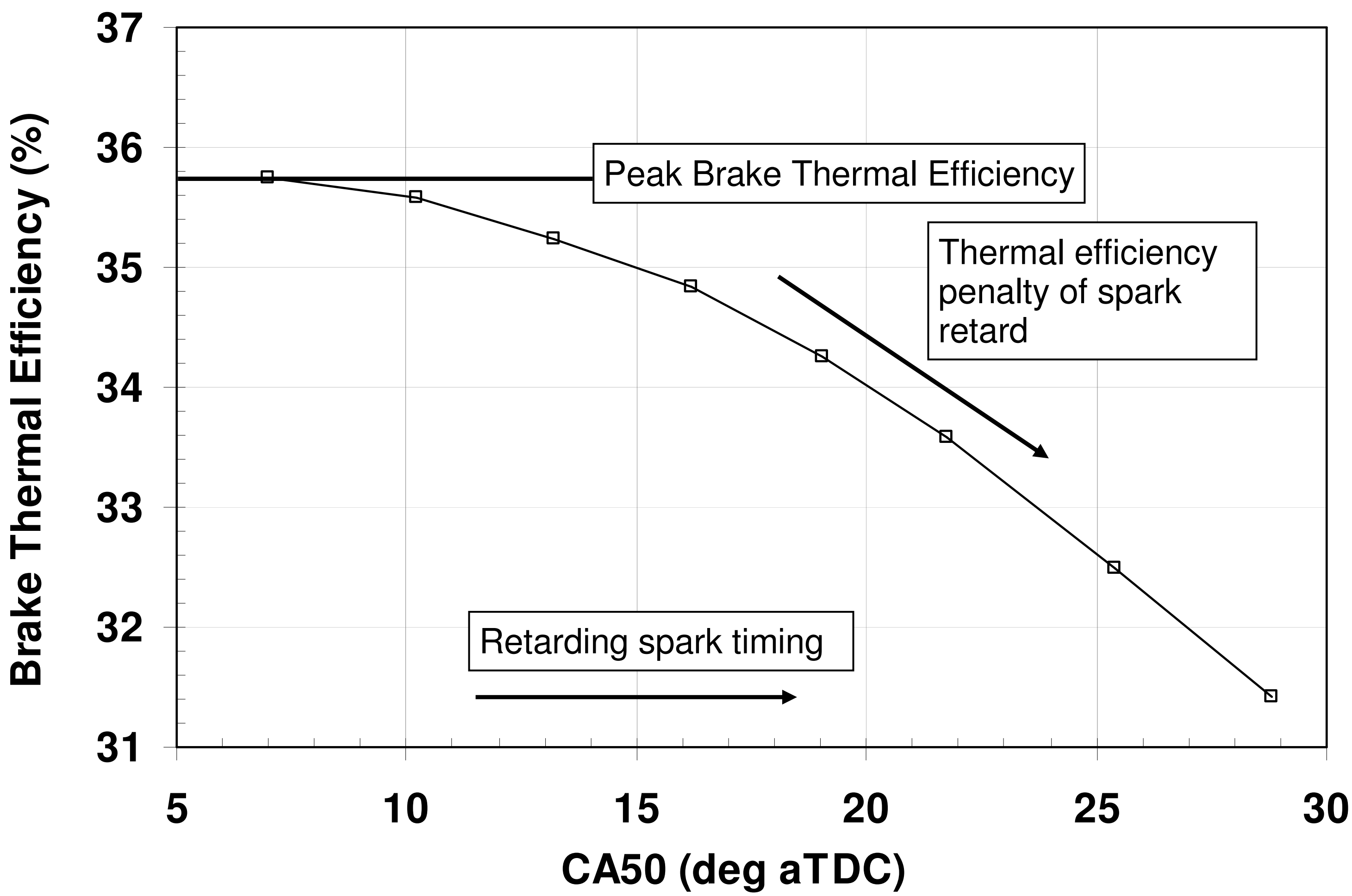
SAE 2009-01-1490

Background – Charge Cooling with Direct Injection of Ethanol



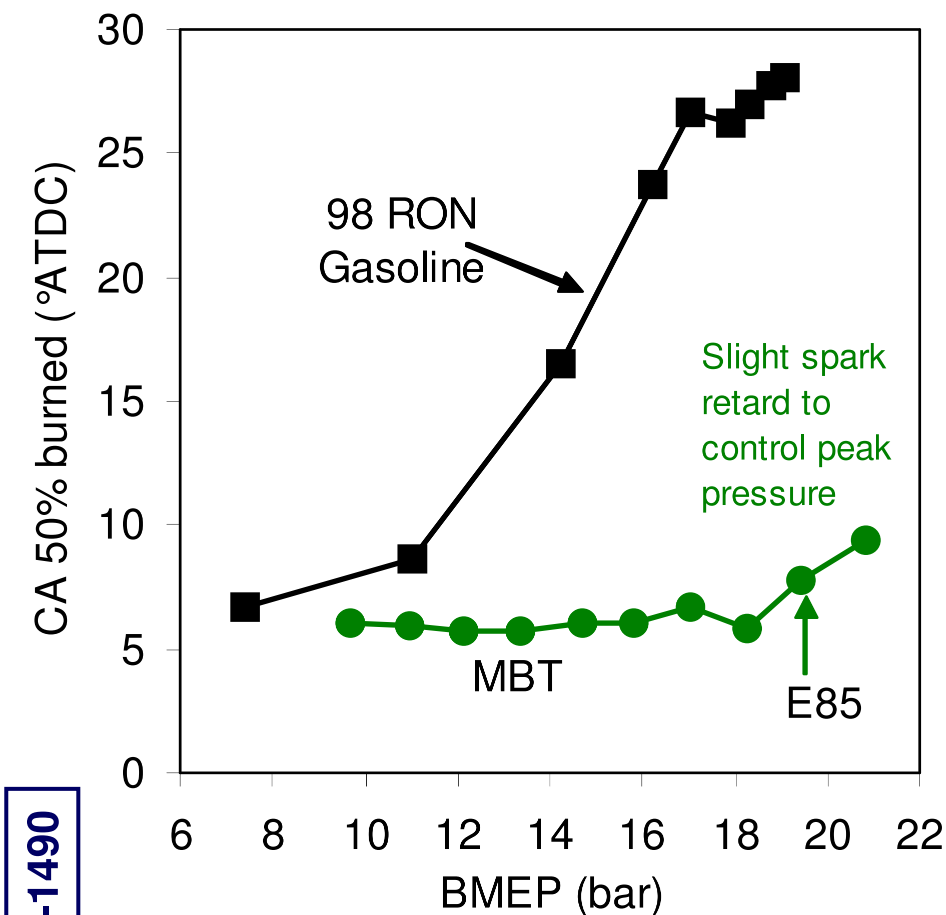
Lower peak unburned gas temperature directly correlates with reduced knock.

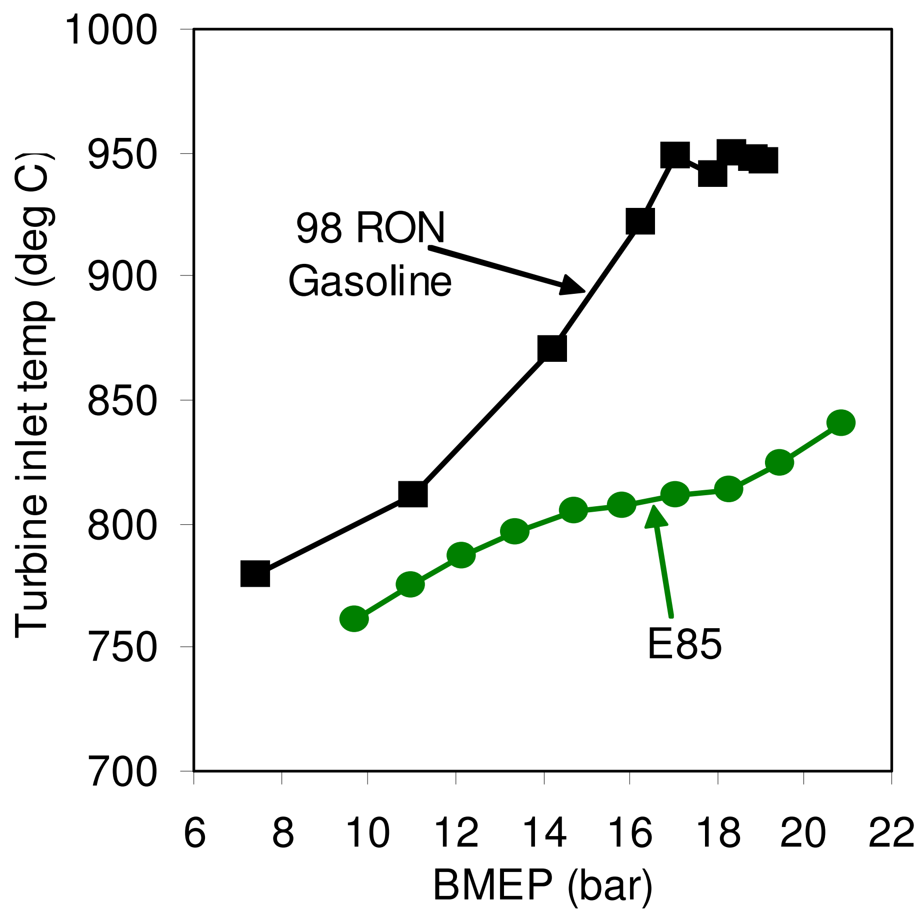
Background – Combustion Phasing



CA50% Burned (deg aTDC) or CA50 (deg aTDC):
Location in Crank Angle degrees after TDC where 50% of the air-fuel mixture has burned. Optimum CA50 for best thermal efficiency occurs ~ 5 - 7 aTDC.

Background - Effect of E85 DI on Knock





Direct injection of E85 is very effective in suppressing knock!

BMEP = Brake Mean Effective Pressure:
A measure of torque per unit of engine displacement expressed in units of pressure (bar).

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Background - Dual Fuel Concept

Rationale:

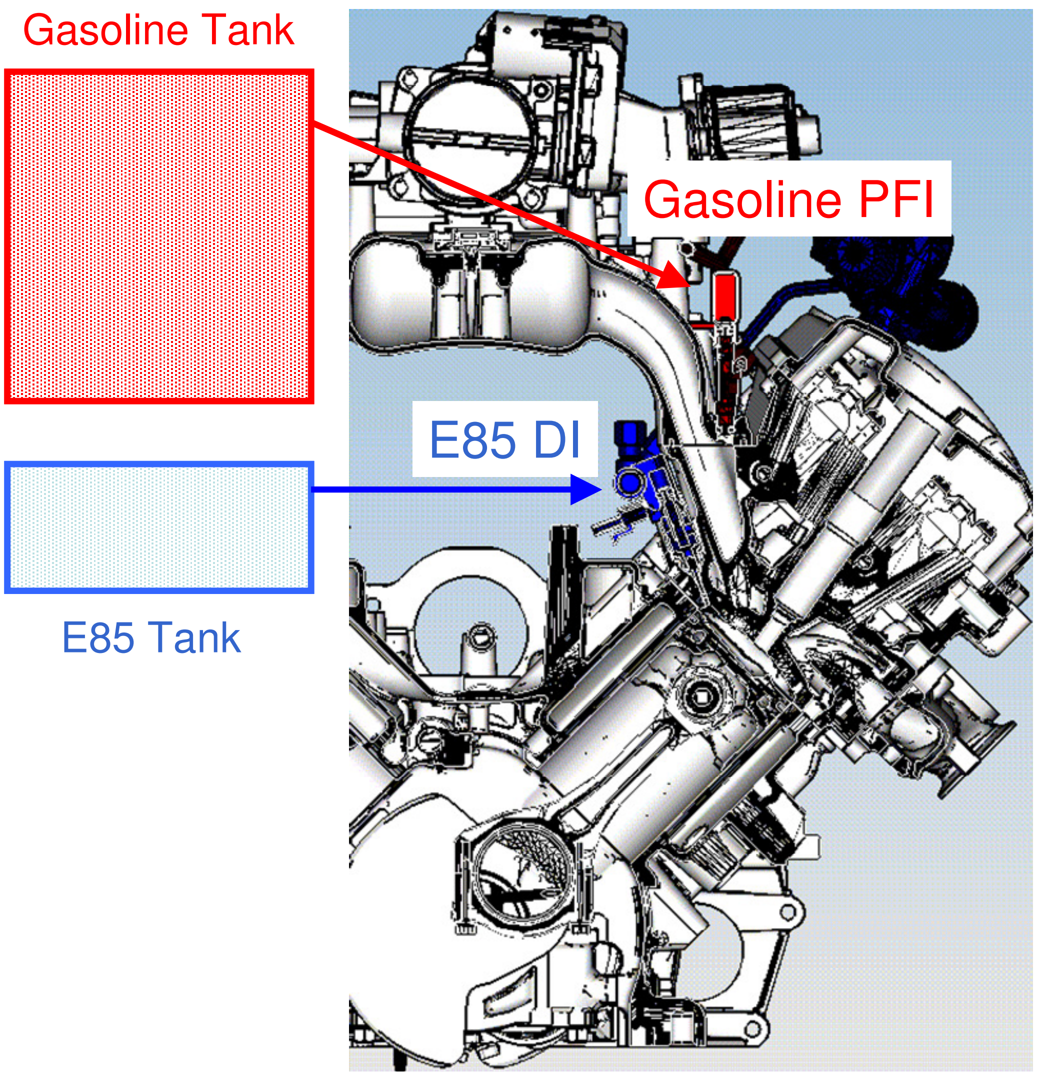
E85 provides large octane benefit with direct injection due to high heat of vaporization and high inherent octane.

This allows knock-free operation at high compression ratio and high BMEP with very high thermal efficiency.

but…

Low E85 heating value per volume is a disadvantage for mpg fuel economy and fuel tank range.

Dual Fuel (E85 DI + Gasoline PFI) Concept



- Combines high load E85 octane benefit with part load gasoline heating value advantage
- First proposed by Cohn, Bromberg, and Heywood of MIT
- Gasoline, with its high heating value per volume, is the primary fuel
- E85 used only as required to avoid knock
- Compression ratio and boost increased
- Higher CR, downsizing, and downspeeding improve efficiency
- Provides maximum leveraging of available ethanol

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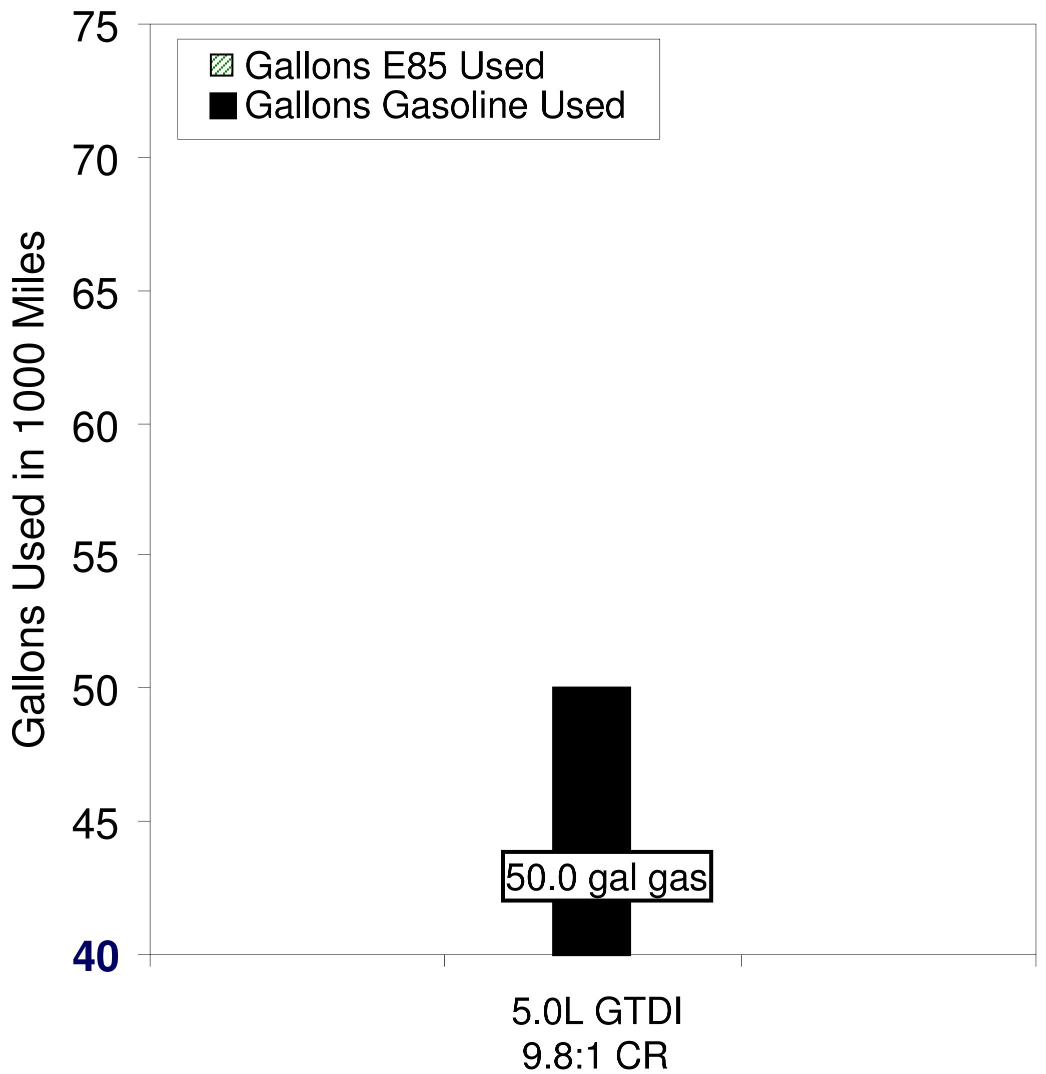
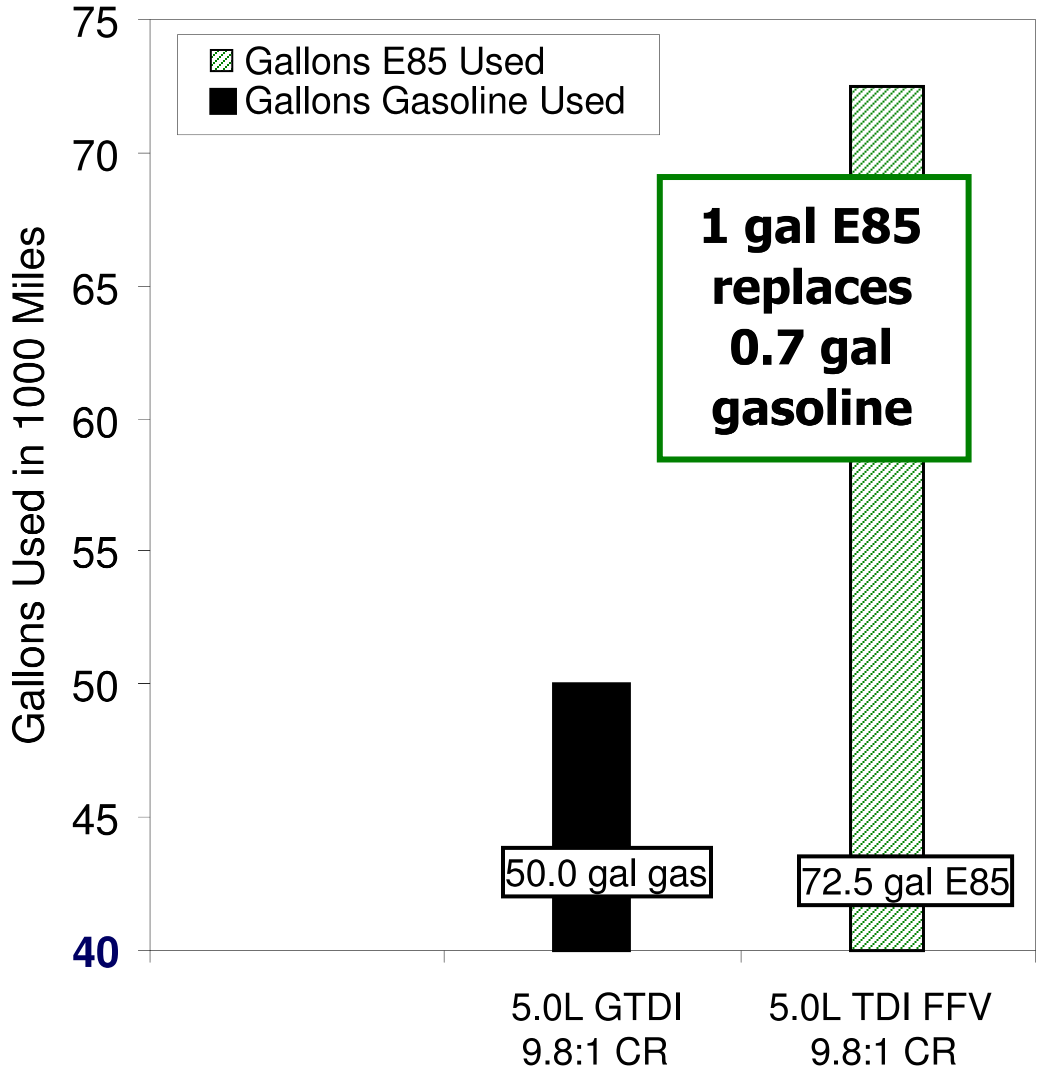
Example Leveraging – EPA M/H Cycle



GTDI = Gasoline Turbocharged Direct Injection

SAE 2009-01-1490

Example Leveraging – EPA M/H Cycle



GTDI = Gasoline Turbocharged Direct Injection

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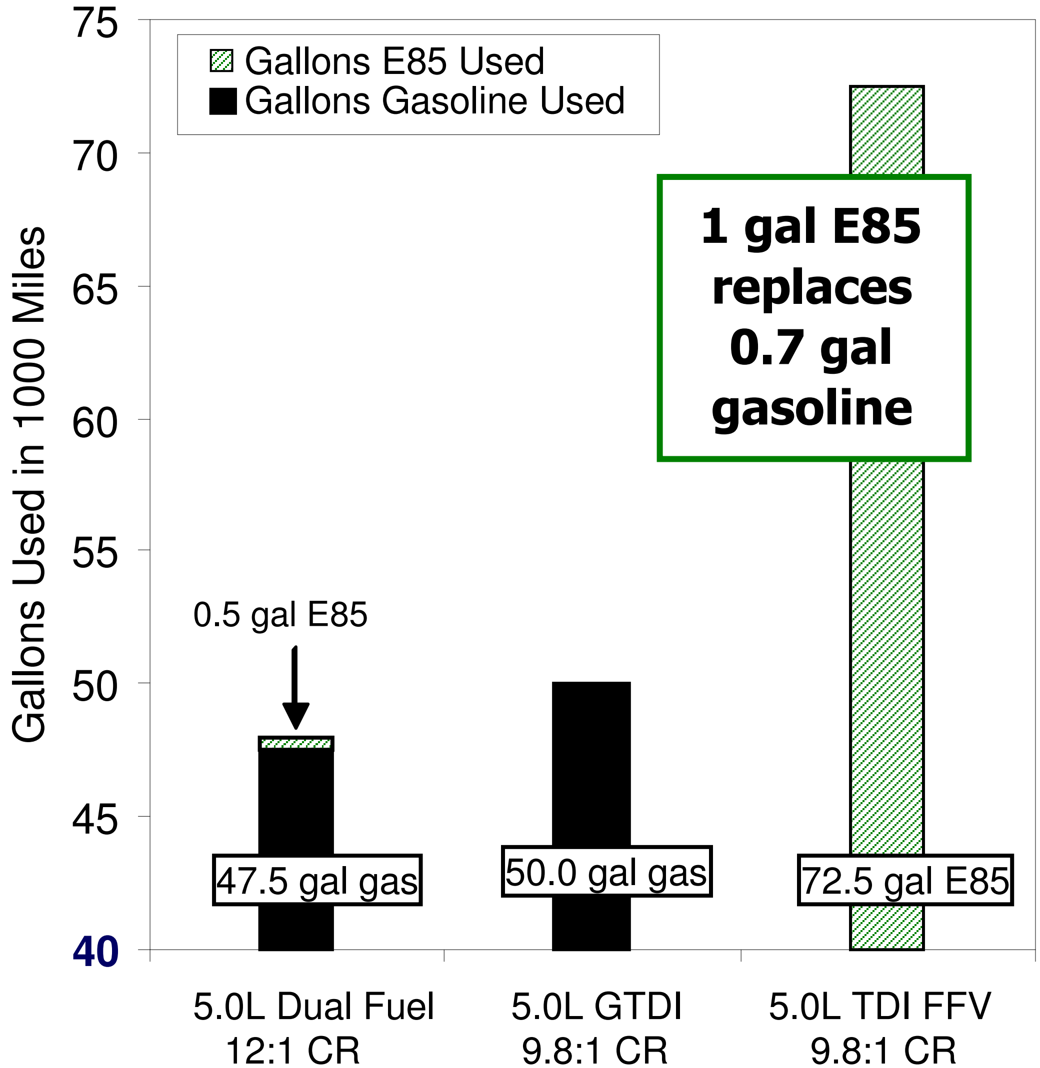
Example Leveraging – EPA M/H Cycle



GTDI = Gasoline Turbocharged Direct Injection

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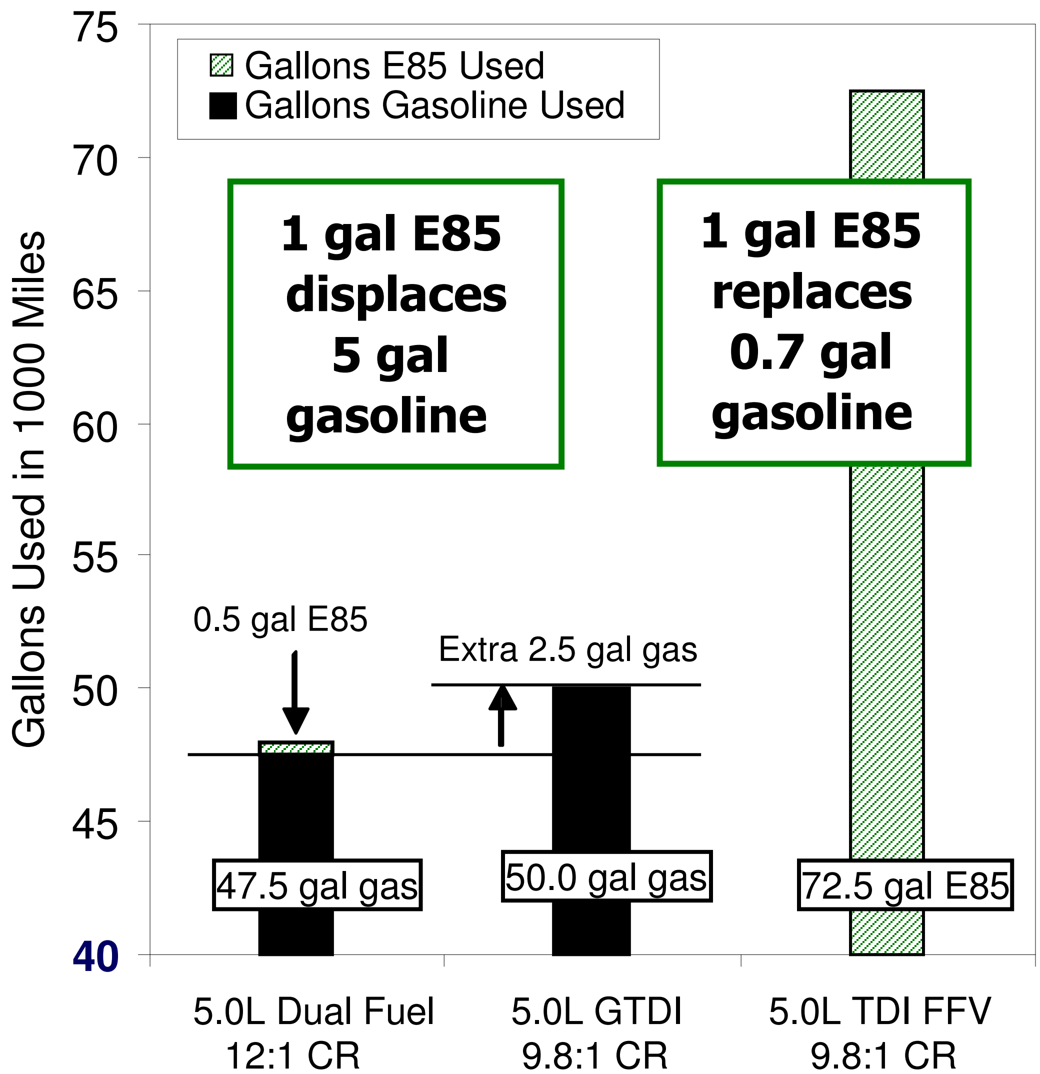
Example Leveraging – EPA M/H Cycle



GTDI = Gasoline Turbocharged Direct Injection

The Dual Fuel (E85 DI + gasoline PFI) concept:

- Makes the engine more efficient in its use of gasoline
- Thereby leveraging the benefit of the available ethanol in reducing gasoline consumption

Note: Leveraging effect is dependent on the drive cycle, and on the amount of compression ratio increase and engine downsizing / downspeeding. 5:1 leveraging is not a general rule-of-thumb.

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Ethanol Optimized Engine Project

Design and develop a new V8 engine for the ethanol optimized engine project.

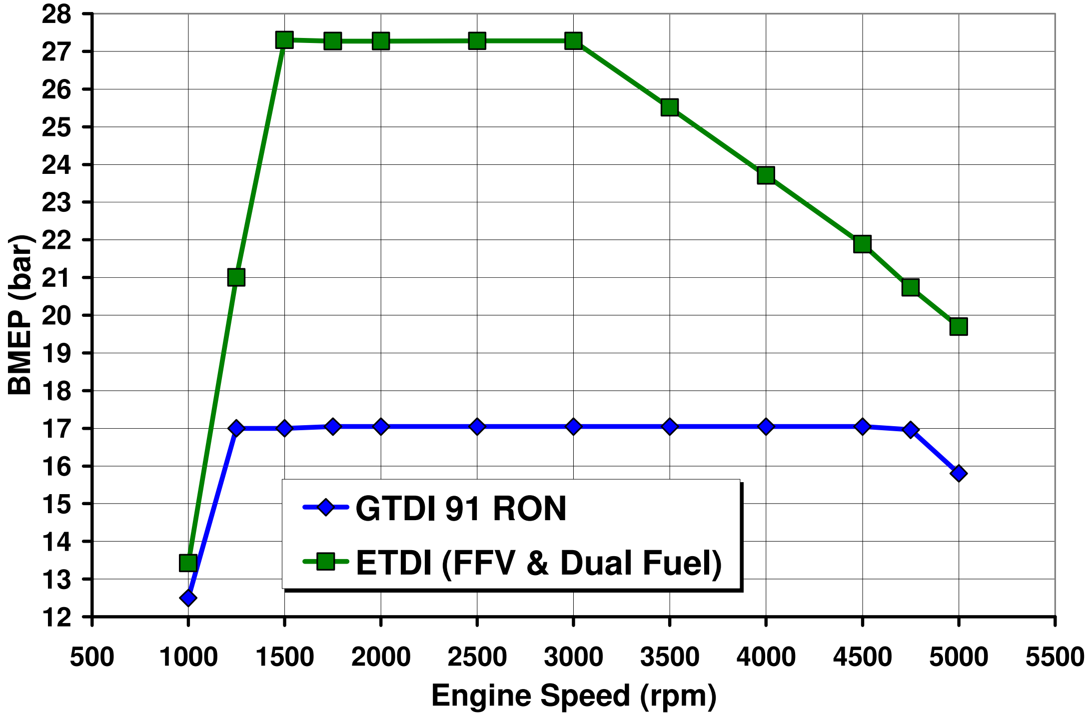
- Dual fuel (E85 Direct Injection + gasoline Port Fuel Injection)
- Twin-turbocharged
- Structure designed for 150 bar peak cylinder pressure
- Twin-Independent variable cam timing
- Roller finger follower valvetrain

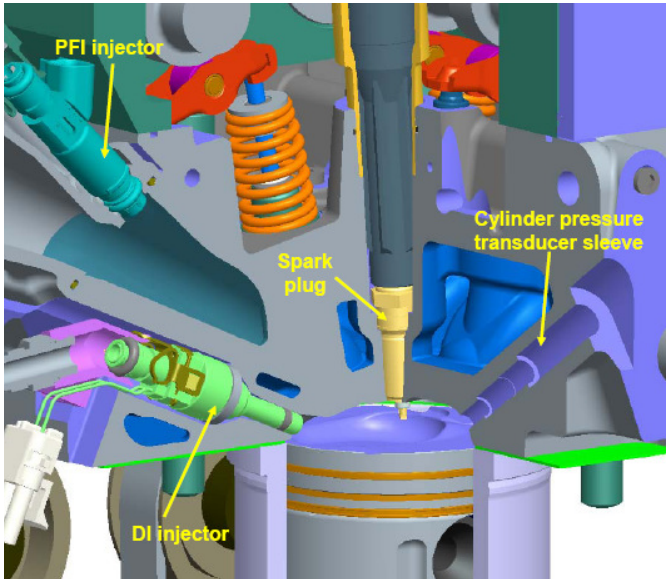
Ethanol Optimized Engine Project
Fueling Alternatives

Fueling alternatives used during engine testing:

- Dual Fuel: E85 direct injection combined with gasoline port fuel injection
  - E85 is used only as required to avoid knock, either at the CA50 for best thermal efficiency or at a specified CA50.
- ETDI: Ethanol Turbocharged Direct Injection
- GTDI: Gasoline Turbocharged Direct Injection

Initial Development Targets

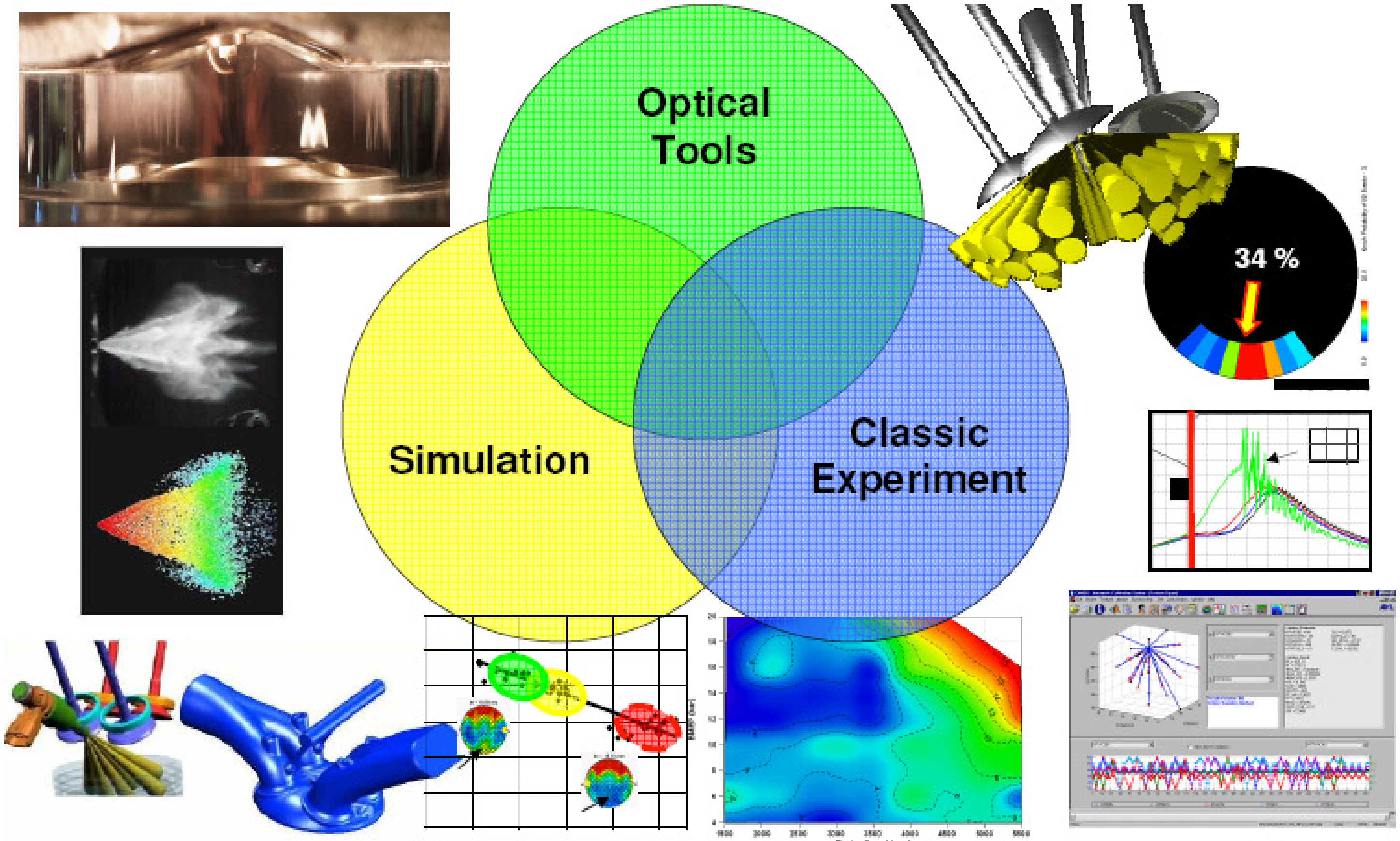




Support flex fuel and dual fuel operation

- Address V8 residual imbalance issues due to blowdown interference
- Maximize low end torque with scavenging with variable cam timing
- Minimize gasoline fuel enrichment at full load (for flex fuel application)
- Minimize cylinder wall wetting with fuel with direct injection
- Develop rapid catalyst heating strategies utilizing dual fuel

Approach

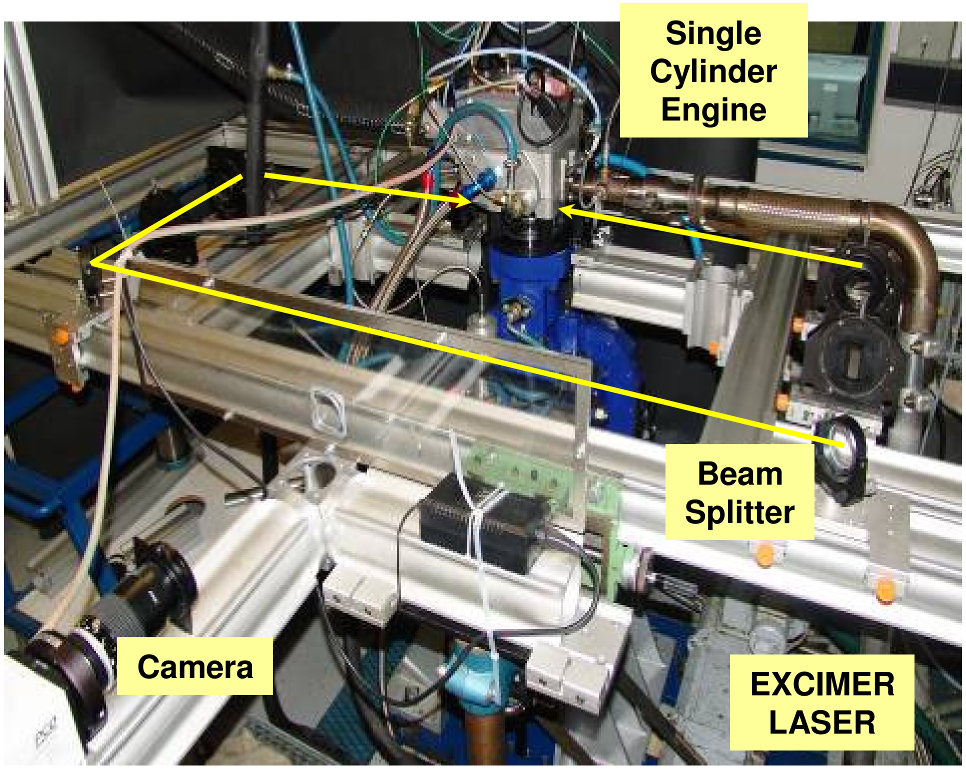


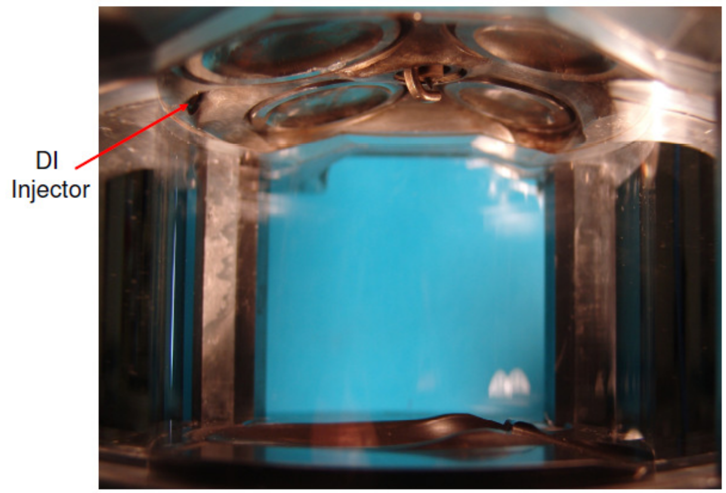
Approach

- 1-D modeling
  - Determine initial cam timings and turbocharger match.
- 3-D CFD, LDA[1] flow rig, optical engine, and conventional single cylinder engine
  - Optimize in-cylinder charge motion, fuel spray, and piston bowl.
- Multi-cylinder engine
  - Develop cam events, variable cam timing strategy, compression ratio, turbocharger matching, and air induction system.
- Multi-cylinder engine mapping
  - Develop vehicle level projections of performance and fuel economy for various driving cycles.
- Transient cold start multi-cylinder engine
  - Optimize starting strategy for low emissions, fast catalyst light-off, and good combustion stability.

[1]Laser Doppler Anemometry

Optical Engine Development





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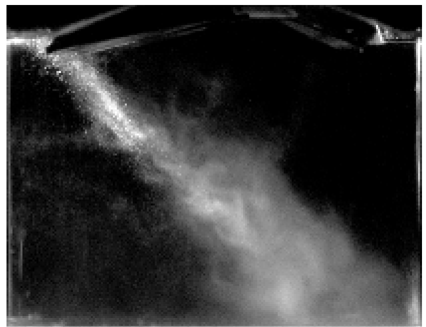
Optical Engine: Laser Induced Fluorescence and Combustion Photography

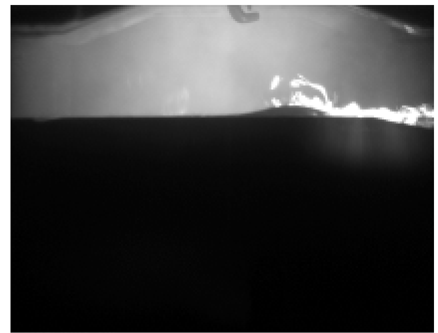
Planar Double Sided LIF Image

Flame Image

Raw Image



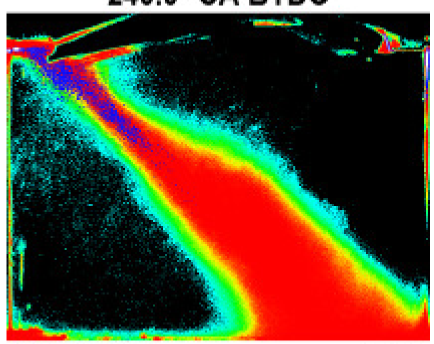
240.0° CA BTDC



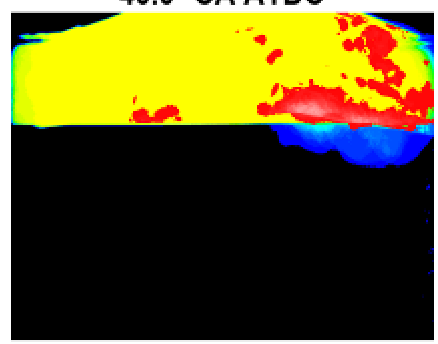
40.0° CA ATDC

Statistical Image Evaluation

240.0° CA BTDC



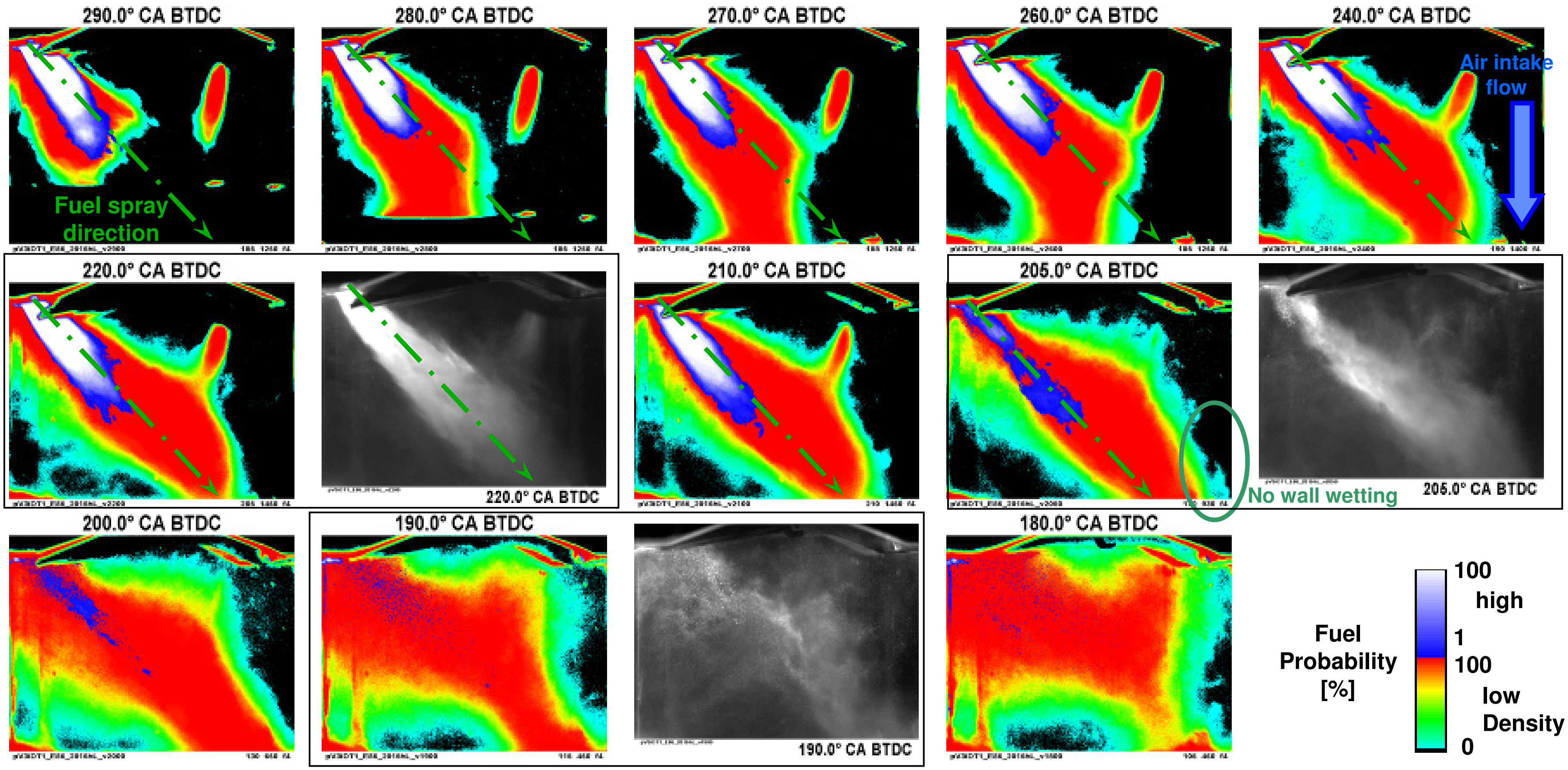
40.0° CA ATDC



The optical engine is used to optimize mixture preparation, eliminate cylinder bore wall wetting, and optimize catalyst heating and cold start.

Optical Engine
2000 RPM Full Load, Ethanol, LIF Images

Satisfactory full load mixture preparation even with E85 flow rates. Significant beneficial fuel spray/air motion interaction even at low speed (where air motion is low) leading to no cylinder bore wall wetting issues.



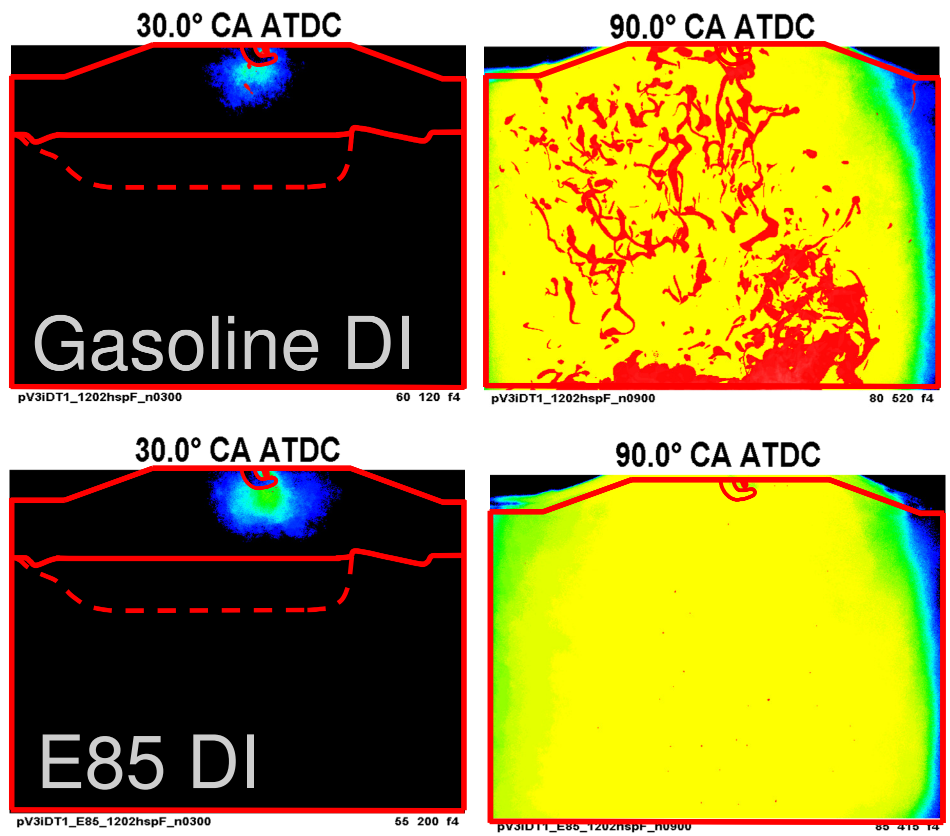
pV3iDT1_E85_2015hL

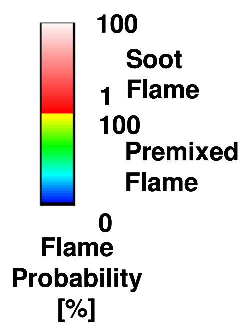
DOE 2009 Merit Review

Optical Engine: Gasoline vs. E85 Combustion During Catalyst Heating

No sooting flames with E85

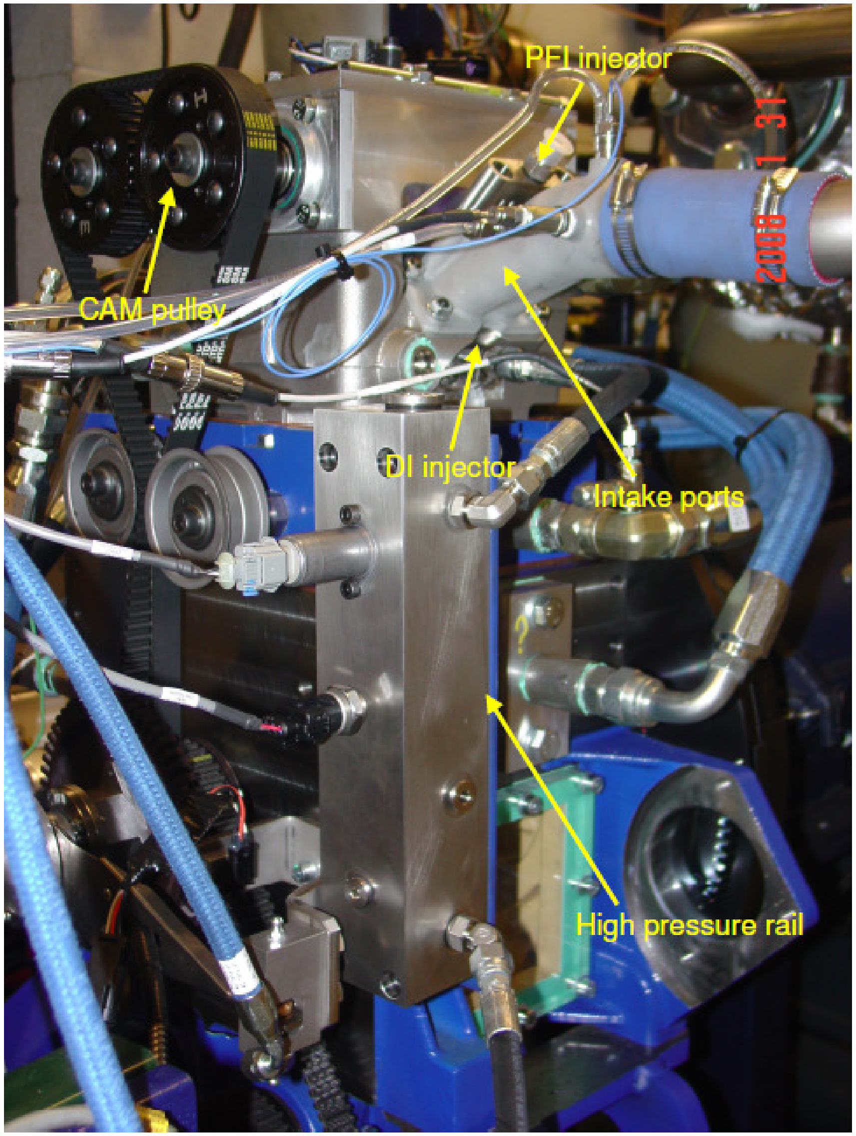
- Ethanol has a single boiling point of 78.3℃, whereas gasoline has a range up to 200℃. Thus E85 vaporizes more readily after impingement on the piston.
- Ethanol is oxygenated which facilitates combustion of rich regions without making soot.





SAE 2010-01-0585

Single Cylinder Engine Development



Single cylinder engine was used to finalize the combustion system prior to procuring multi-cylinder engine components.

Multi-Cylinder Engine Development

Engine Configuration

90°V8	Dual Fuel
Bore-stroke ratio: 0.88	Twin turbochargers
Compression ratio: 9.5:1 and 12:1	Twin Independent VCT

Multi-Cylinder Engine Development
Alternative Paths

Two alternative paths investigated for the dual fuel engine.

9.5:1 Compression Ratio

Normal functional performance on gasoline (but reduced relative to E85) if E85 is not available.

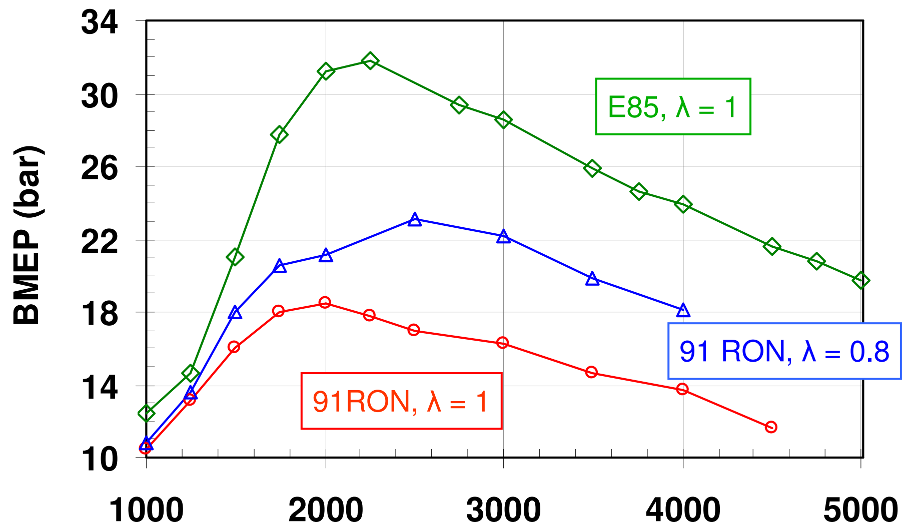
12:1 Compression Ratio

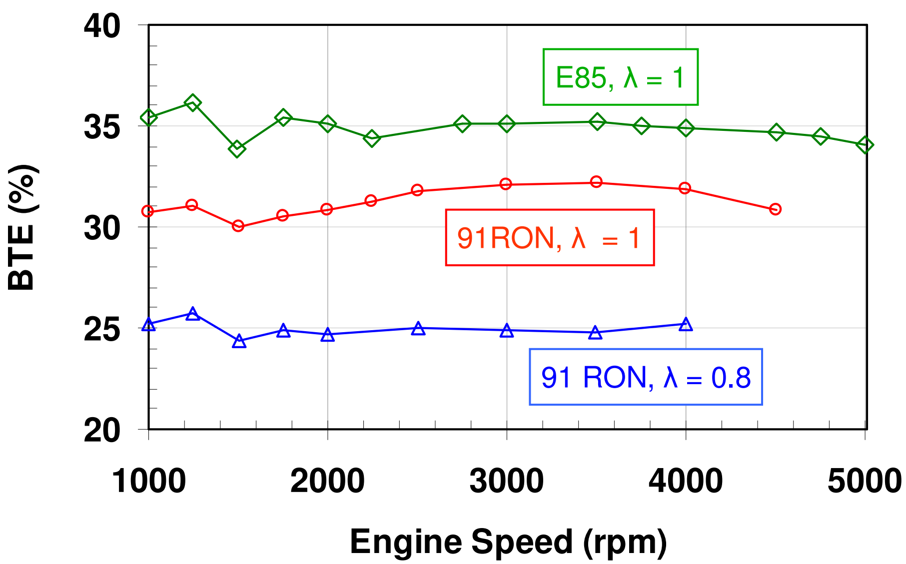
Greater improvement in efficiency, but compromised performance on gasoline due to knock if E85 is not available.

Ethanol Optimized Engine

Both paths utilize downspeeding/downsizing for improved efficiency.

Multi-Cylinder Engine Full Load Comparison
ETDI (E85) vs. GTDI (91 RON) at 9.5:1 CR



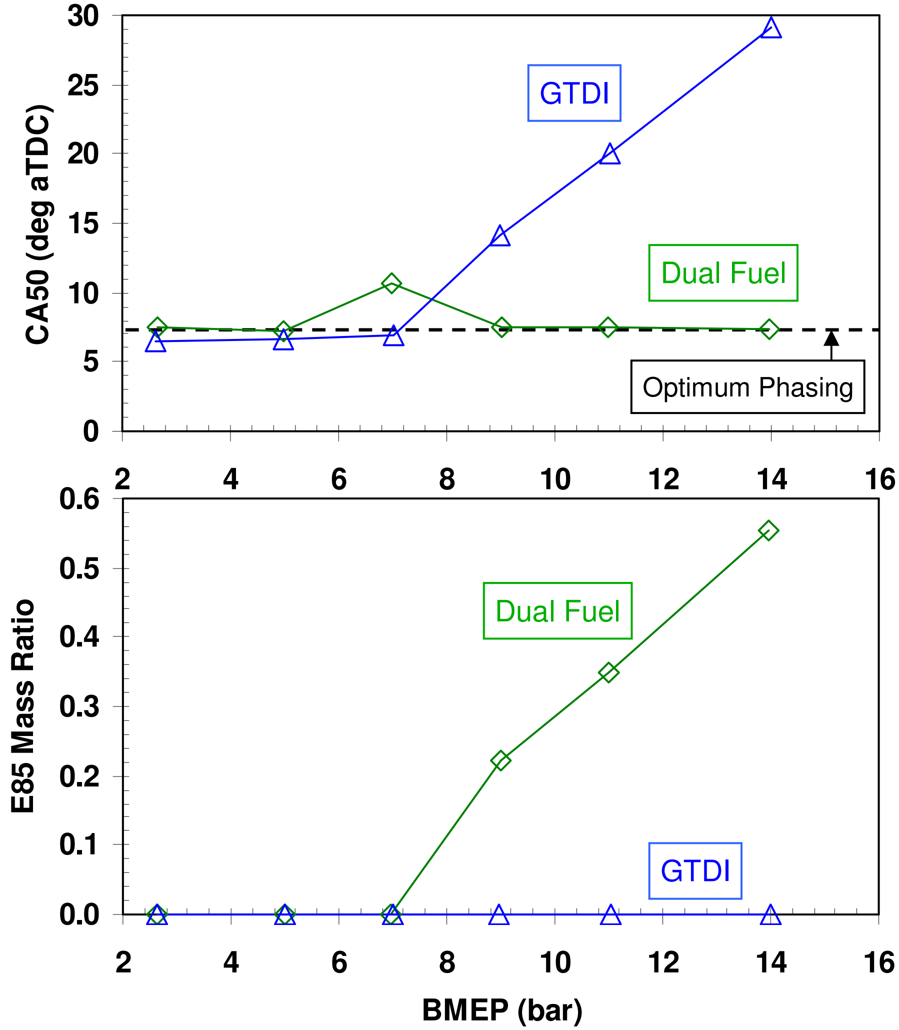


E85 allows stoichiometric operation over the entire engine map:

- Maintains TWC function for US06 and all off-cycle conditions.
- Provides very high power for Dyno Cert applications.
- Achieves high brake thermal efficiency.
- Avoids fuel economy penalty due to enrichment.

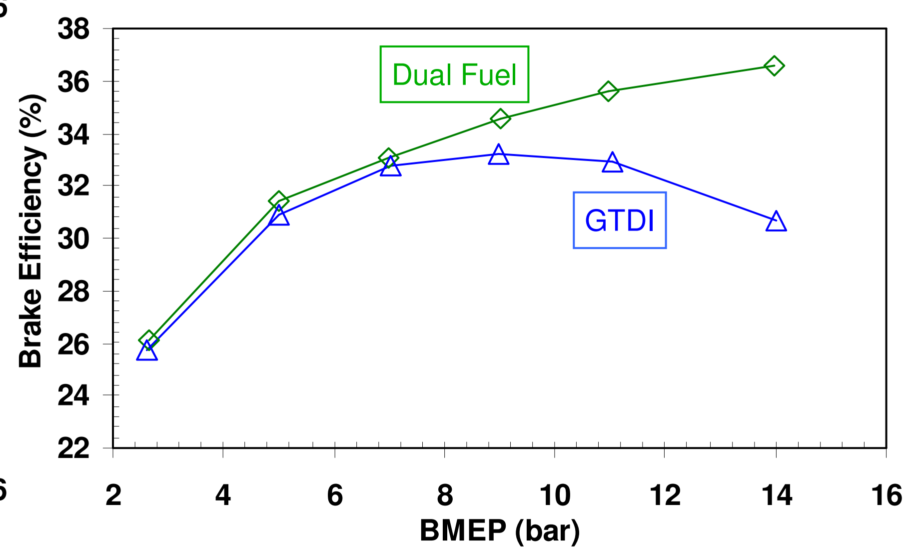
Note: Higher BTE is possible with E85 with increased compression ratio.

Multi-Cylinder Engine at Part Load
E85 Consumption for the Dual Fuel Engine at 1500 RPM

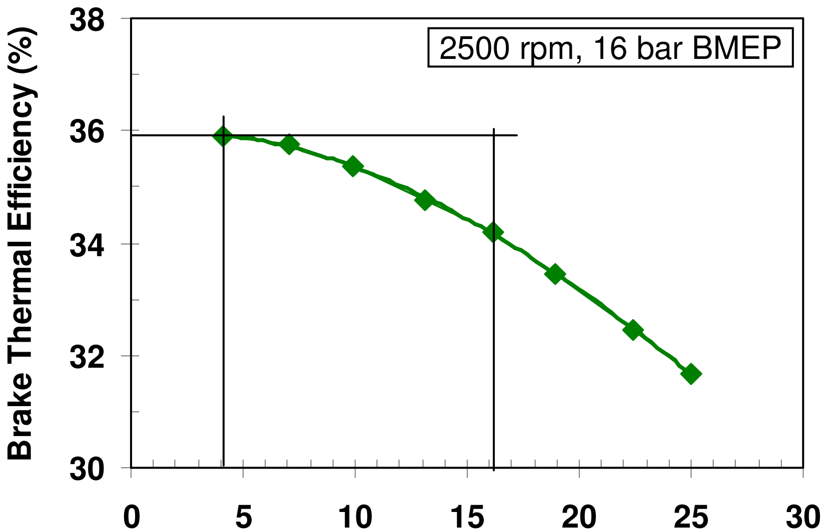


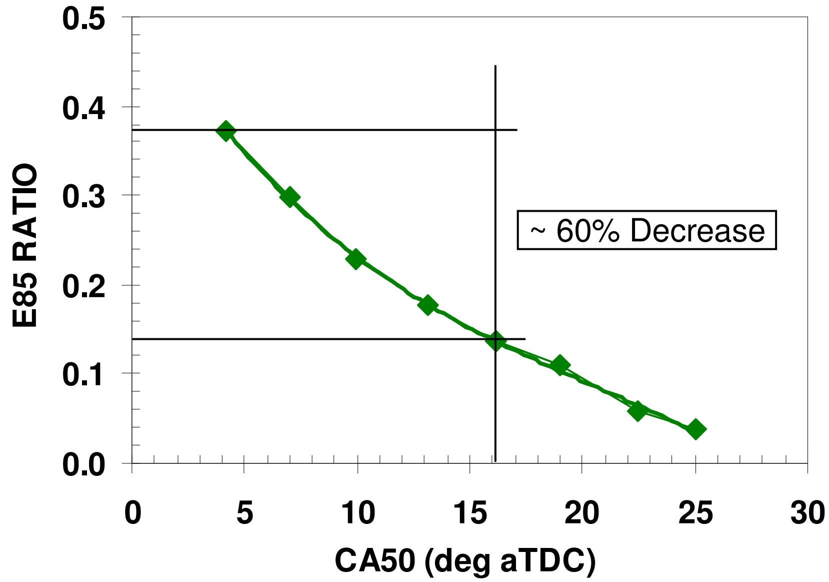
- E85 is directly injected only as required to avoid knock at optimum CA50.
- Enables high brake thermal efficiency as BMEP is increased.

Note: E85 Mass Ratio = E85 flow rate / total fuel flow rate (E85 + gasoline)



Dual Fuel Engine: Effect of Combustion Phasing E85 Consumption for High Load Conditions

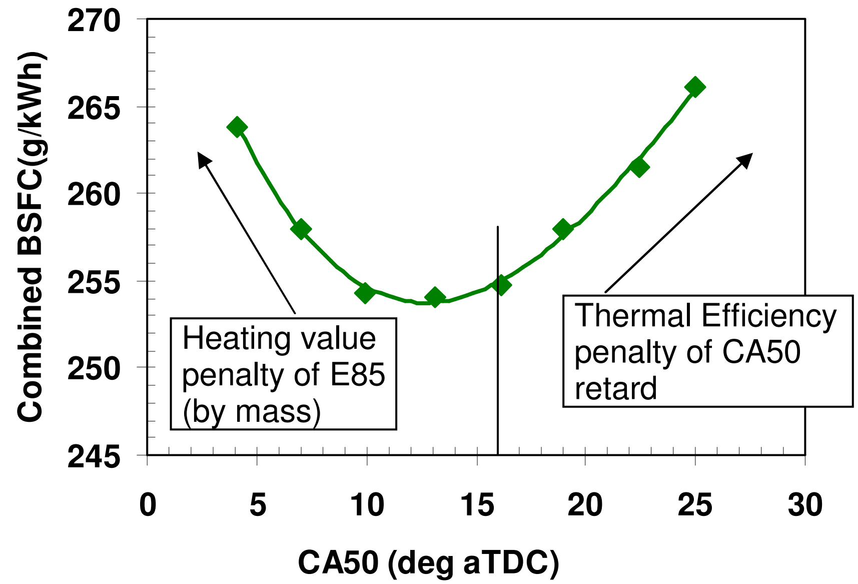




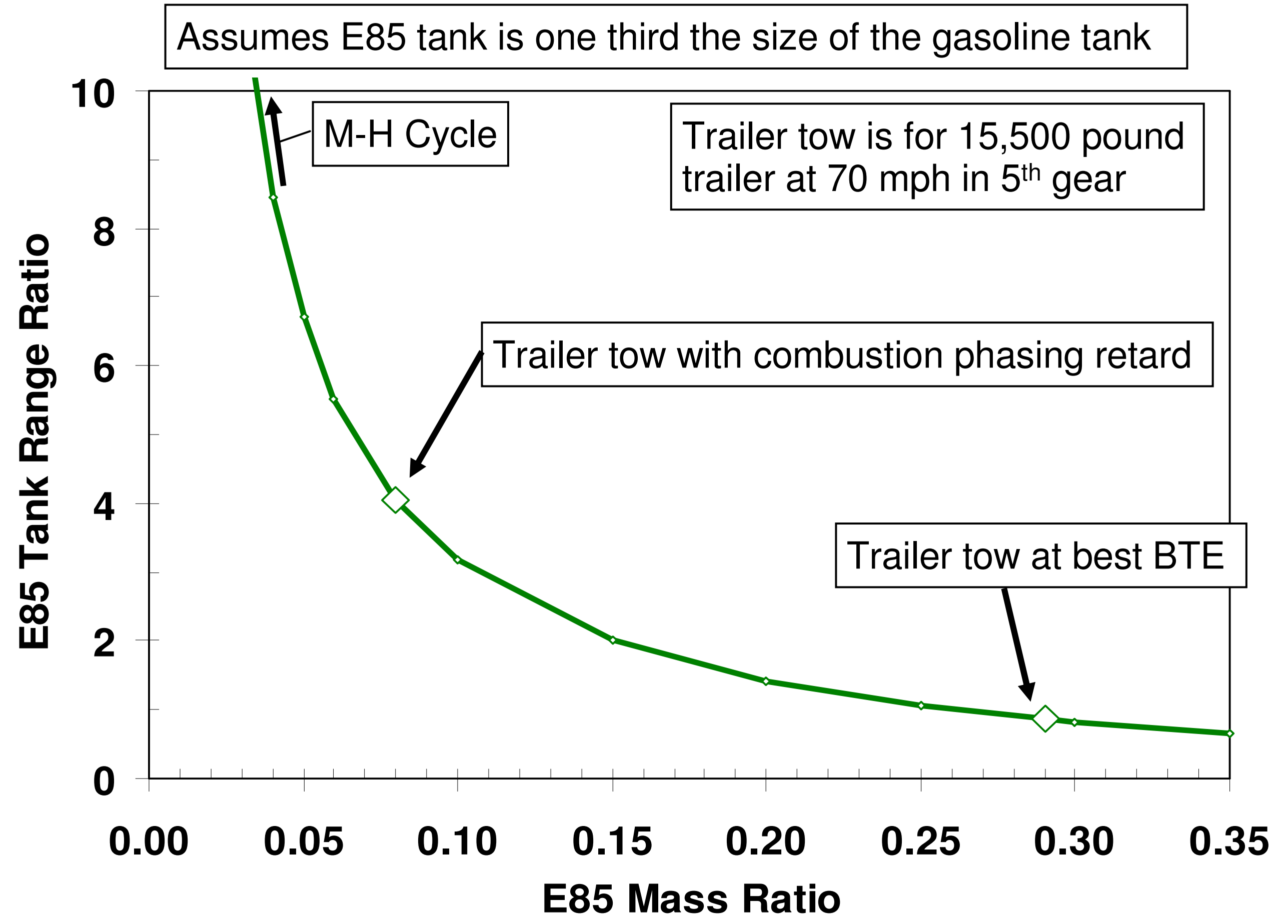
Moderate combustion phasing retard:

- Significantly reduces amount of E85 required to avoid knock.
- Increases E85 fuel tank range.
- Minimizes combined (gasoline + E85) fuel consumption.

Note: Combined BSFC = (E85 mass flow rate + gasoline mass flow rate)/brake power

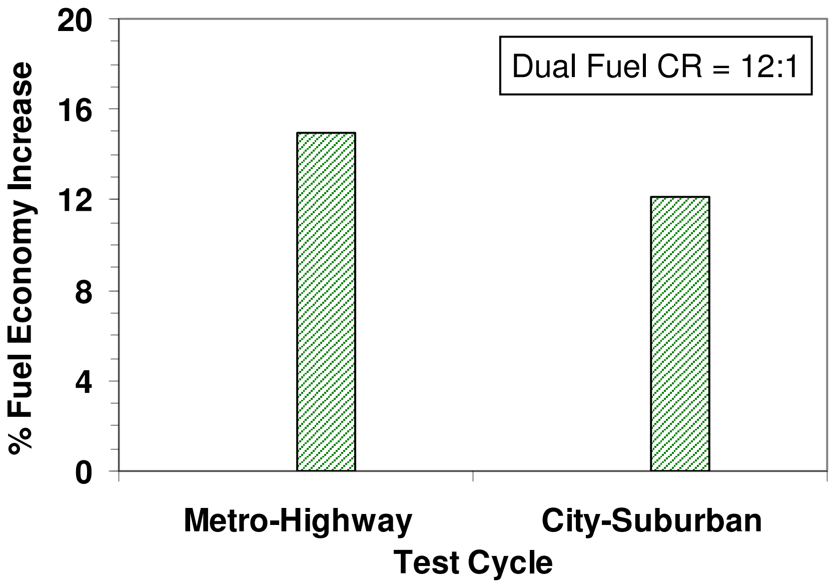


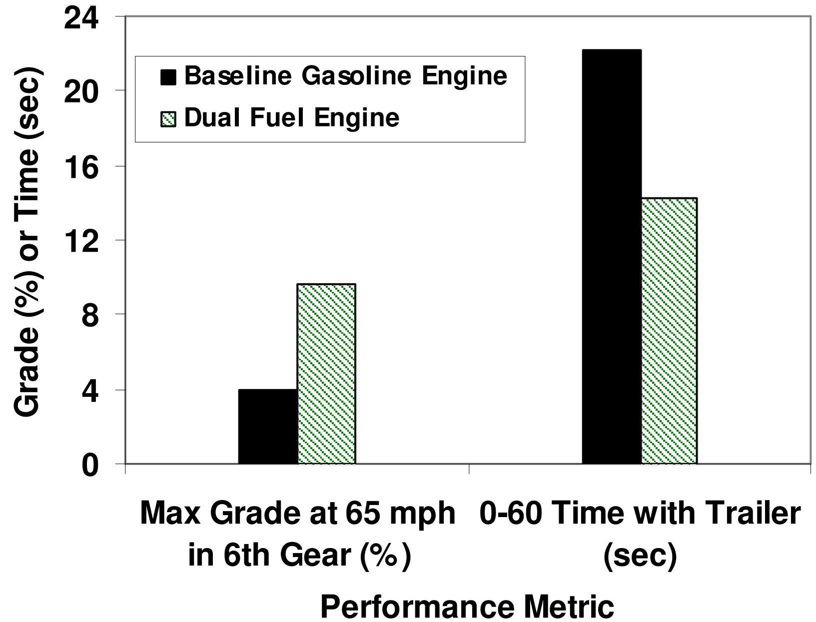
Dual Fuel Engine
E85 Tank Range in F-Series



E85 tank range ratio = range on E85 tank / range on gasoline tank
E85 mass ratio = E85 mass flow rate / total fuel mass flow rate (E85 + gasoline)

Comparison to Baseline Gasoline Engine
Vehicle Simulation Estimated Results for F-Series





The dual fuel engine provides improved fuel economy (mpg) and dramatically improved performance relative to the baseline gasoline engine.

Vehicle simulation results based on multi-cylinder engine data adjusted to 12:1 compression ratio.

Note: City-Suburban is a Ford test cycle for used pickup trucks.

Summary

- A dual fuel twin-turbocharged engine with structure capable of 150 bar peak cylinder pressure was designed and developed.
- Combined 3D-CFD, LDA flow rig, optical engine, and single cylinder engine development was used for optimization of direct injection mixture preparation & combustion processes.
- Direct injection of E85 allows operation at stoichiometry at very high BMEP levels with high thermal efficiency.
- E85 results in minimal soot emissions due to increased vaporization after piston impingement and oxygen content.
- Moderate combustion phasing retard can be used to increase E85 fuel tank range under towing conditions while minimizing overall fuel consumption (gasoline + E85).

Summary (continued)

- The dual fuel engine:
  - Combines the heating value per volume advantage of gasoline with the high load octane advantage of E85.
  - Provides improved efficiency via higher compression ratio and increased BMEP which allows greater levels of downsizing and downspeeding.
  - Significantly leverages the use of ethanol in reducing gasoline consumption and CO_2 emissions.
- Successful implementation of the dual fuel engine depends on:
  - Convenient availability of E85.
  - Customer acceptance of filling two fuel tanks.

Future Work in 2011

- Development and assessment of cold starting strategy for the dual fuel engine on multi-cylinder transient engine dynamometer.
- Evaluation and mapping of the dual fuel engine at 12:1 compression ratio:
  - Fuel efficiency
  - Full load performance
  - E85 consumption and range
- Refinement and final assessment of vehicle level attributes.

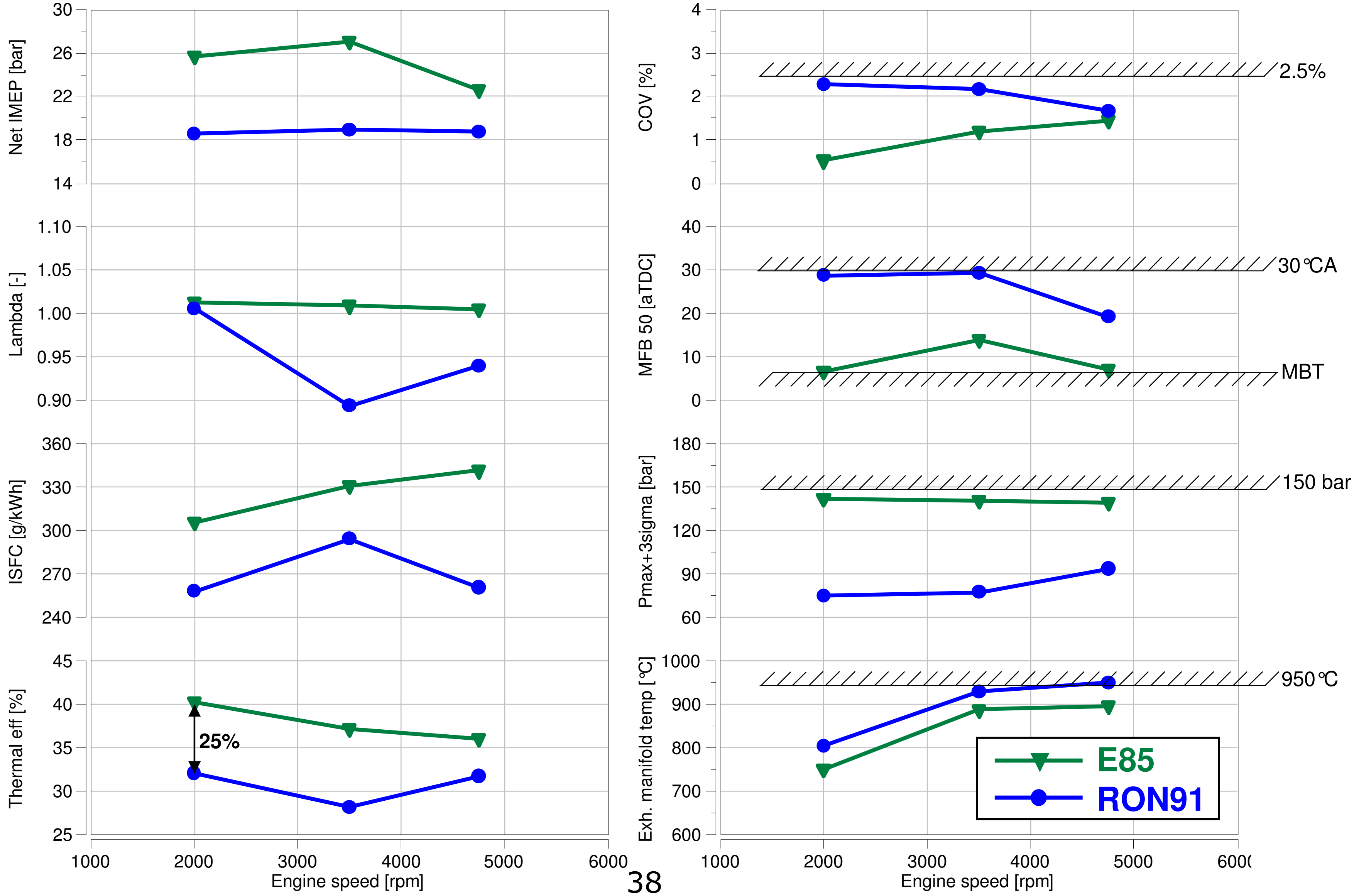
Thank you for your attention.

Questions?

Backup Slides

Single Cylinder Engine: E85 vs. 91 RON

DI E85 operation permits MBT ignition (where not peak pressure limited) without requiring fuel enrichment even at much higher loads than gasoline. This leads to significant efficiency increase!



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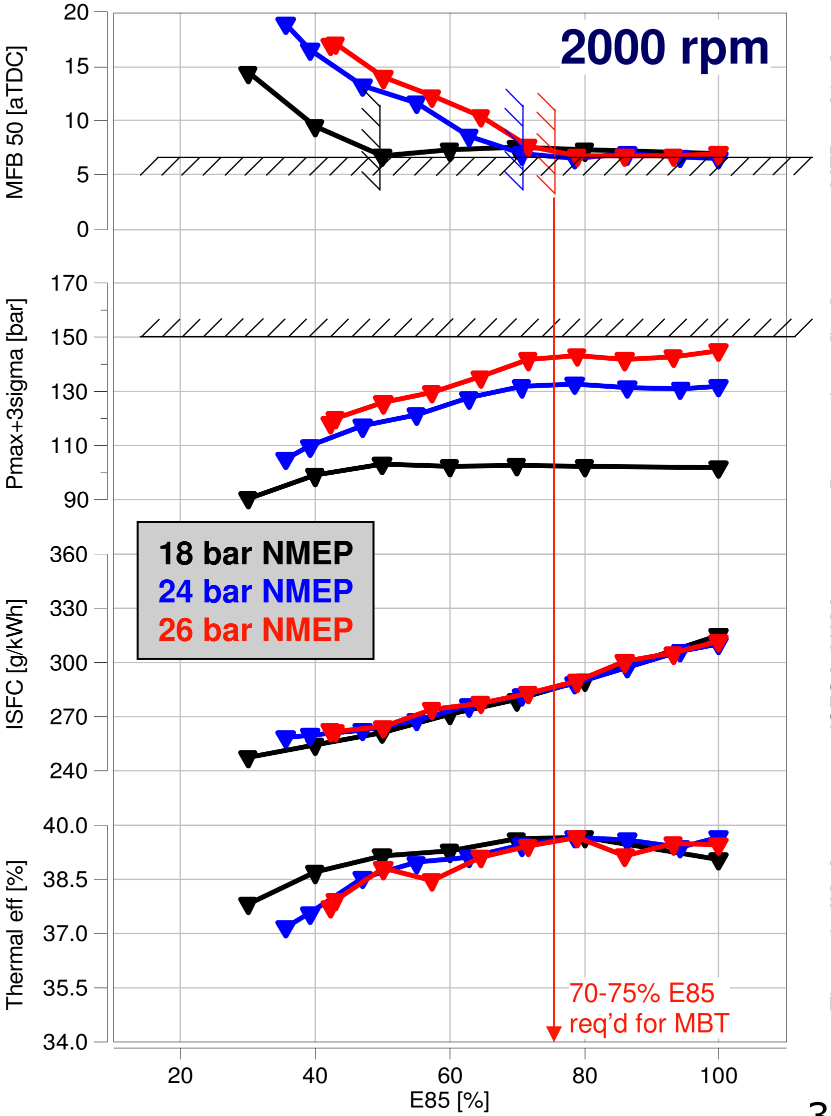
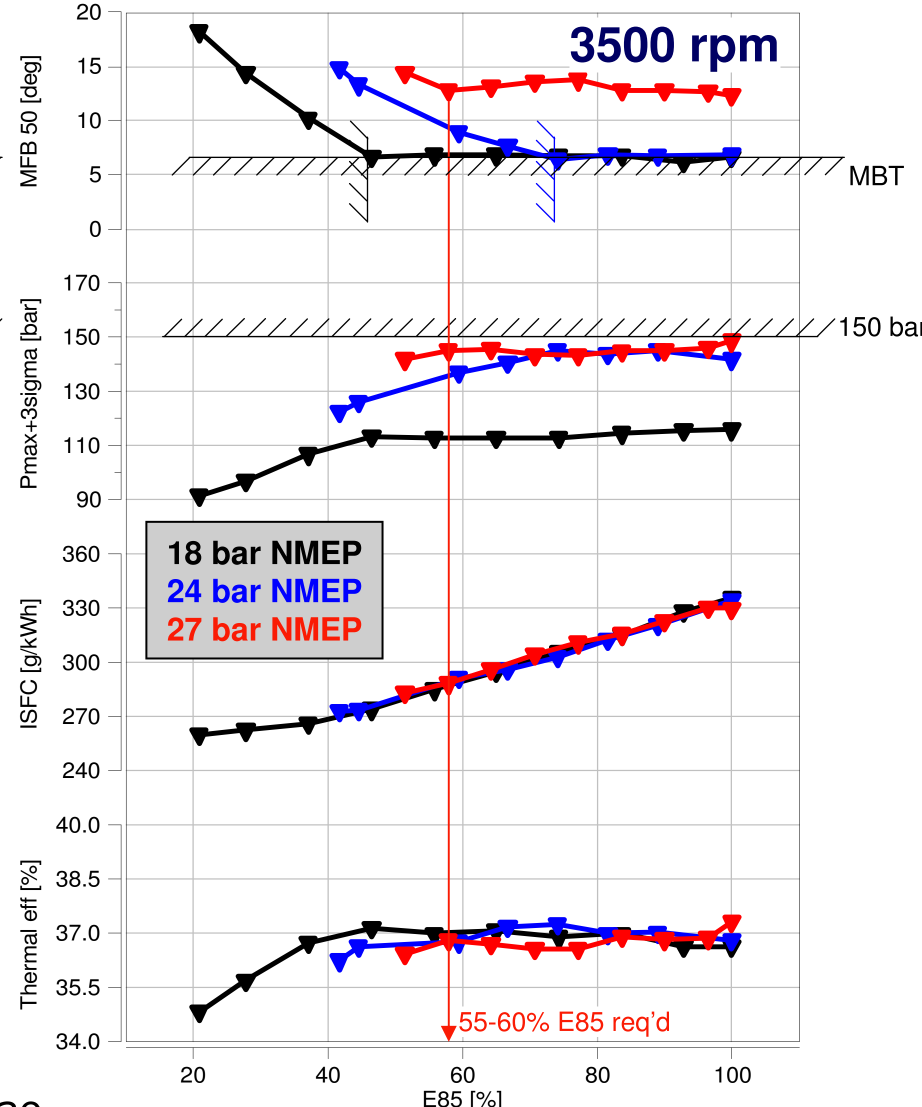
Single Cylinder Engine: Dual Fuel E85 DI % Sweeps

Less than 100% E85 DI required to hold MBT ignition at high BMEP – minimizes E85 consumption increasing E85 range. Reduced E85 requirement when P_{max} limited at higher speeds.





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Effect of Leveraging
Net Energy Value of Ethanol

$$\text{Energy ratio} = \frac{\text{energy content of ethanol}}{\text{energy to produce ethanol}} = 1.67^{1}$$

EER = Effective energy ratio of ethanol used in Dual Fuel engine with leveraging of 5:1 (as an example):

$$\text{EER} = \frac{\text{energy content of saved gasoline}}{\text{energy to produce ethanol}} = 14$$

For leveraging of 5:1, 14 MJ of gasoline energy are saved for every 1 MJ of energy used to produce corn ethanol.

[1]Shapouri, Hosein, Duffield, James, McAloon, Andrew, and Wang, Michael, "The 2001 Net Energy Balance of Corn-Ethanol", 2004.