Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development

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Ford Research and Advanced Engineering

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Project ID: ACE065

Overview

Research and Advanced Engineering

- Timeline
  - Project Start 10/01/2010
  - Project End 12/31/2014
  - Completed 76%
- Total Project Funding
  - DOE Share $15,000,000.
  - Ford Share $15,000,000.
  - Funding in FY2013 $ 4,911,758.
  - Funding in FY2014 $ 2,428,972.
- Barriers
  - Gasoline Engine Thermal Efficiency
  - Gasoline Engine Emissions
  - Gasoline Engine Systems Integration
- Partners
  - Lead Ford Motor Company
  - Support Michigan Technological University (MTU)

Relevance

- Ford Motor Company has invested significantly in Gasoline Turbocharged Direct Injection (GTDI) engine technology in the near term as a cost effective, high volume, fuel economy solution, marketed globally as EcoBoost technology.

- Ford envisions further fuel economy improvements in the mid & long term by further advancing the EcoBoost technology.
  - Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
  - Advanced lean combustion w/ direct fuel injection & advanced ignition
  - Advanced boosting systems w/ active & compounding components
  - Advanced cooling & aftertreatment systems

Objectives

- Ford Motor Company Objectives:
  - Demonstrate 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics.
  - Demonstrate vehicle is capable of meeting Tier 3 SULEV30 emissions on FTP-75 cycle.

- MTU Objectives:
  - Support Ford Motor Company in the research and development of advanced ignition concepts and systems to expand the dilute / lean engine operating limits.

Approach

Research and Advanced Engineering

- Engineer a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, including:
  - Aggressive engine downsizing in a mid-sized sedan from a large V6 to a small I4
  - Mid & long term EcoBoost technologies
    - Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
    - Advanced lean combustion w/ direct fuel injection & advanced ignition
    - Advanced boosting systems w/ active & compounding components
    - Advanced cooling & aftertreatment systems
  - Additional technologies
    - Advanced friction reduction technologies
    - Advanced engine control strategies
    - Advanced NVH countermeasures
- Progressively demonstrate the project objectives via concept analysis / modeling, single-cylinder engine, multi-cylinder engine, and vehicle-level demonstration on chassis rolls.

Milestone Timing

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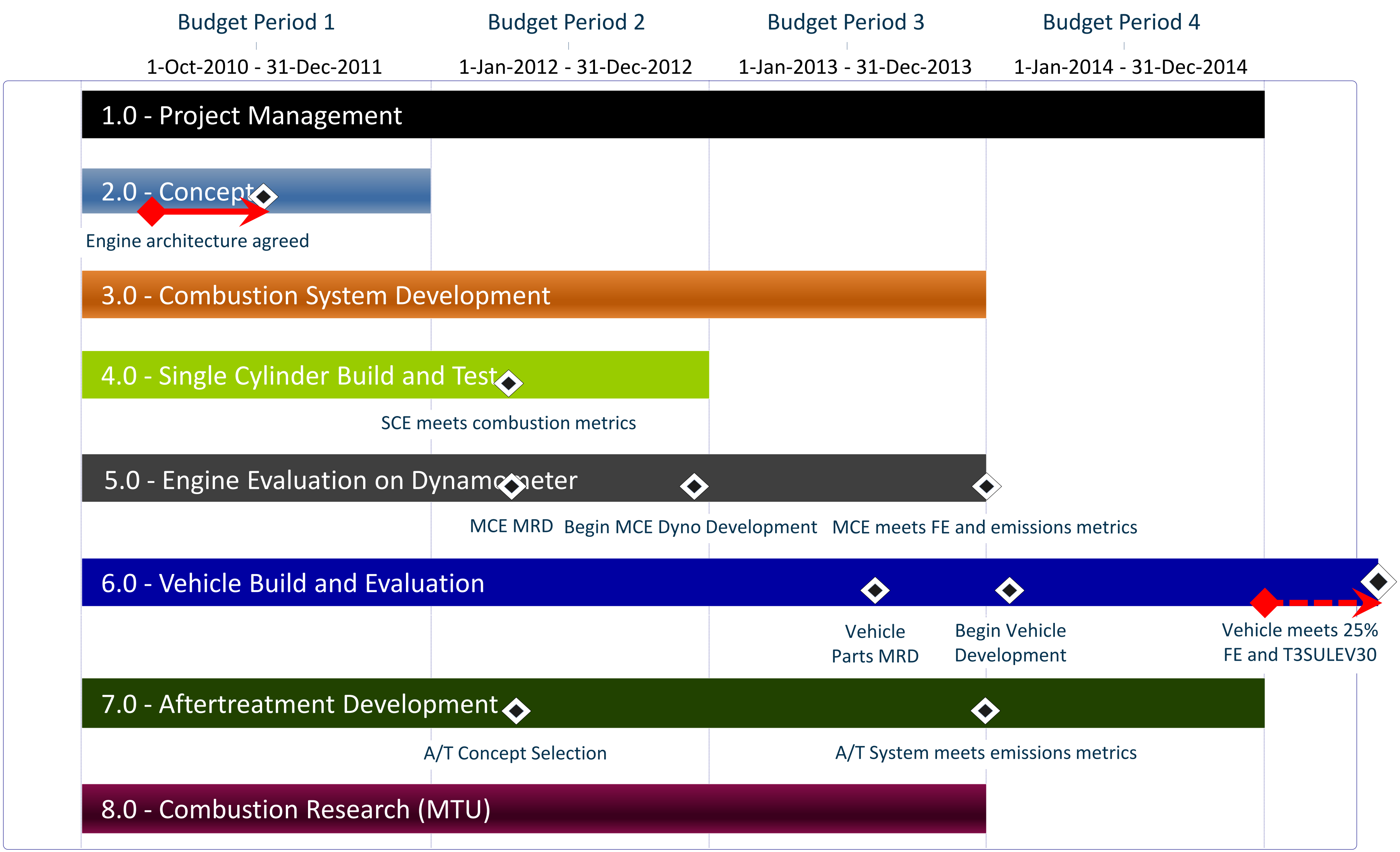

Project Assumptions

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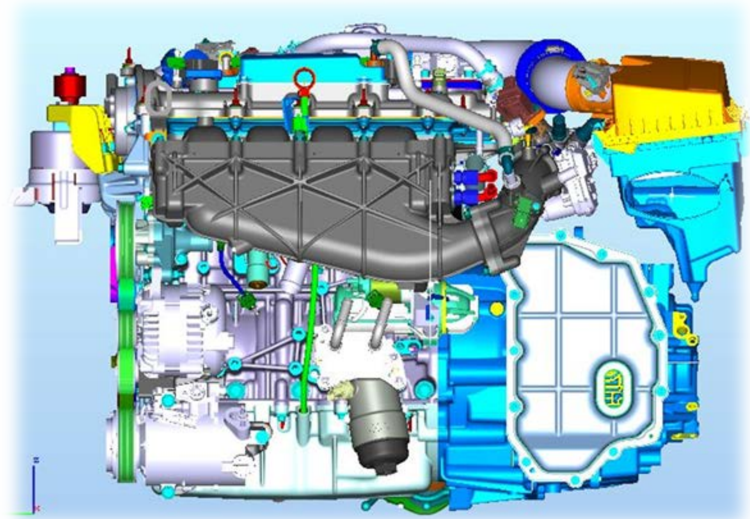
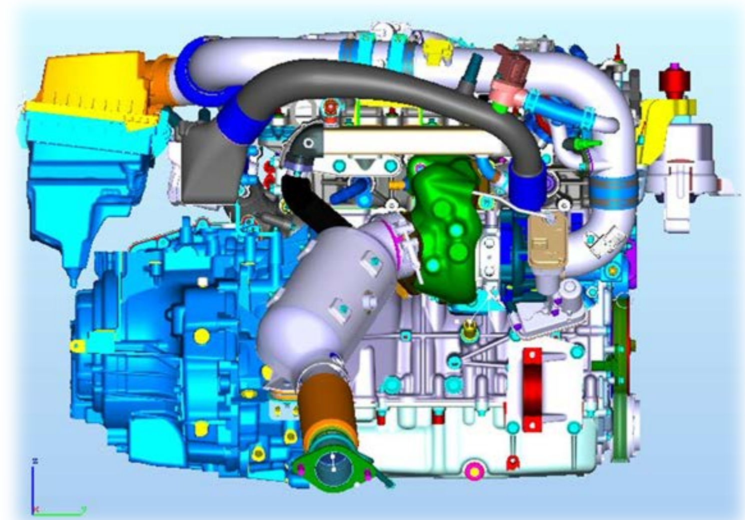
- Attribute Assumptions

Peak Power =	80 kW / L @ 6000 rpm
Peak Torque =	20 bar BMEP @ 2000 - 4500 rpm
Naturally Asp Torque @ 1500 rpm =	8 bar BMEP
Peak Boosted Torque @ 1500 rpm =	16 bar BMEP
Time-To-Torque @ 1500 rpm =	1.5 s
As Shipped Inertia =	0.0005 kg-m^2 / kW



- Architecture Assumptions

Displacement / Cylinder =	565 cm^3
Bore & Stroke =	87.5 & 94.0 mm
Compression Ratio =	11.5:1
Bore Spacing =	96.0 mm
Bore Bridge =	8.5 mm
Deck Height =	222 mm
Max Cylinder Pressure (mean + 3σ) =	100 bar
Max Exhaust Gas Temperature =	960°C
Fuel Octane =	98 RON



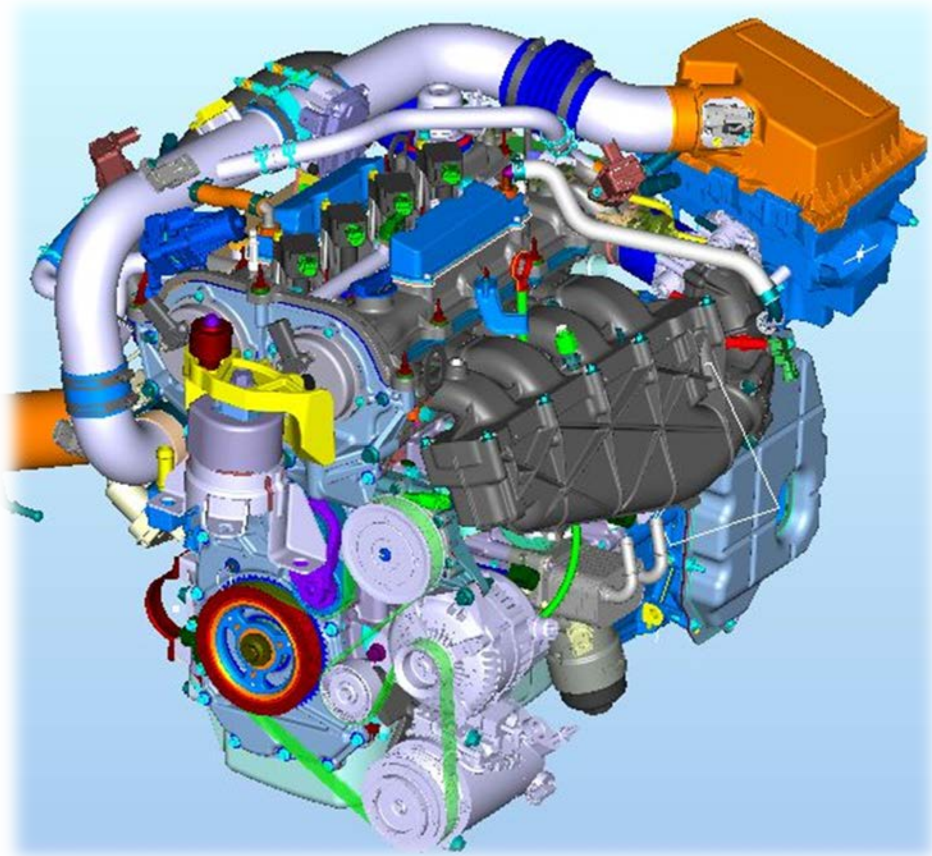
Project Assumptions

Research and Advanced Engineering

- Systems Assumptions
  - Transverse central DI + ignition w/ intake biased multi-hole injector
  - Twin scroll turbocharger w/ scroll control valve + active wastegate
  - Low pressure, cooled EGR system
  - Composite intake manifold w/ integrated air-water charge air cooler assembly
  - Split, parallel, cross-flow cooling with integrated exhaust manifold
  - Integrated variable displacement oil pump / balance shaft module
  - Compact RFF valvetrain w/ 12 mm HLA
  - Roller bearing cam journals on front, all other locations conventional
  - Electric tiVCT

  - Torque converter pendulum damper
  - Active powertrain mounts
  - Assisted direct start, ADS
  - Electric power assisted steering, EPAS

  - Three way catalyst, TWC
  - Lean NOx aftertreatment, LNT + SCR



Concept Evaluation

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- Detailed, cycle-based CAE analysis of fuel economy contribution of critical technologies

Architecture / System Assumption	% Fuel Economy	
3.5L V6 ⇨ 2.3L I4 High Expansion Ratio Architecture	+	**15.6% - Engine Architecture / Downsizing**
583 ⇨ 565 cm³ Displacement / Cylinder	~	
1.07 ⇨ 0.93 Bore / Stroke	~	
10.3:1 ⇨ 11.5:1 Compression Ratio	+	
PFI ⇨ Transverse Central DI	-	
iVCT ⇨ Electric tiVCT	+	
Split, Parallel, Cross-Flow Cooling & Integrated Exhaust Manifold	+	**7.8% - Engine & As-Installed Systems**
Variable Displacement Oil Pump & Roller Bearing Cam Journals	+	
DAMB ⇨ Compact RFF Valvetrain	+	
3.5L V6 ⇨ 2.3L I4 Idle & Lugging Limits	-	
Torque Converter Pendulum Damper & Active Powertrain Mounts	+	
Assisted Direct Start, ADS	+	
Electric Power Assisted Steering, EPAS	+	
Active Wastegate	+	**4.4% - Air Path / Combustion**
Low Pressure, Cooled EGR System	+	
Lean NOx Aftertreatment, LNT + SCR	+	
Torque Converter & Final Drive Ratio	+	**0.2% - Engine Match**
Total	**28.0**	

Accomplishments

 #1 – Combustion System / Mechanical Verification

 #2 – Cold Start Emissions Development

 #3 – Steady State Mapping

 #4 – Mechanical Friction Study ⇨ NVH Study

Phase 1 Build
3-4Q’12

 #5 – Performance Development

 #6 – Thermal Management Studies

 #7 – Mechanical Development Studies

 #8 – Spare ☺

Phase 2 Build
2-3Q’13

Phase 3 Build
3Q’13

 #9

 #10

 #11

 #12

$\xrightarrow[\text{Vehicles (4)}]{\text{Calibration}}$

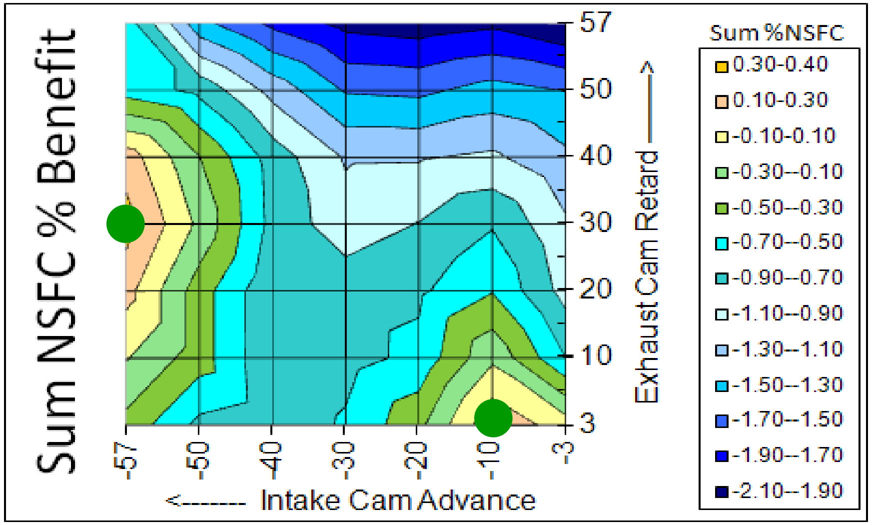
Accomplishments

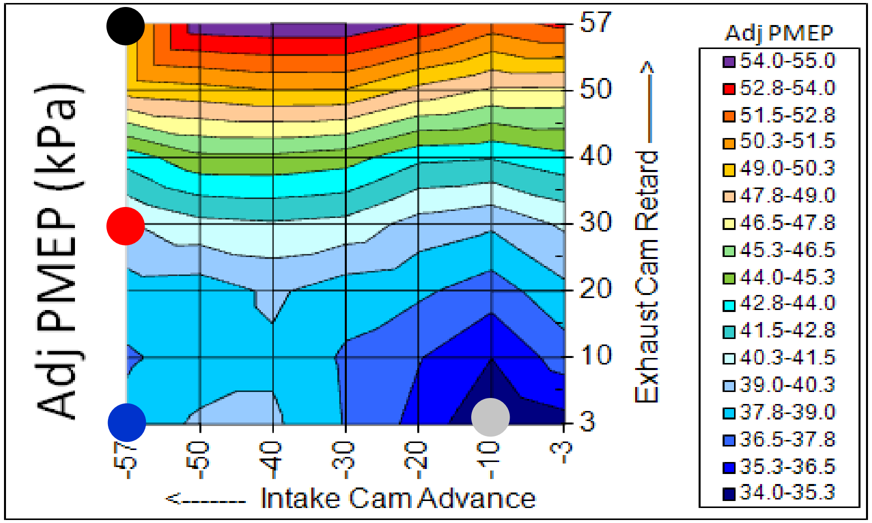
2.3L MiGTDI Pre-XO Engine #1

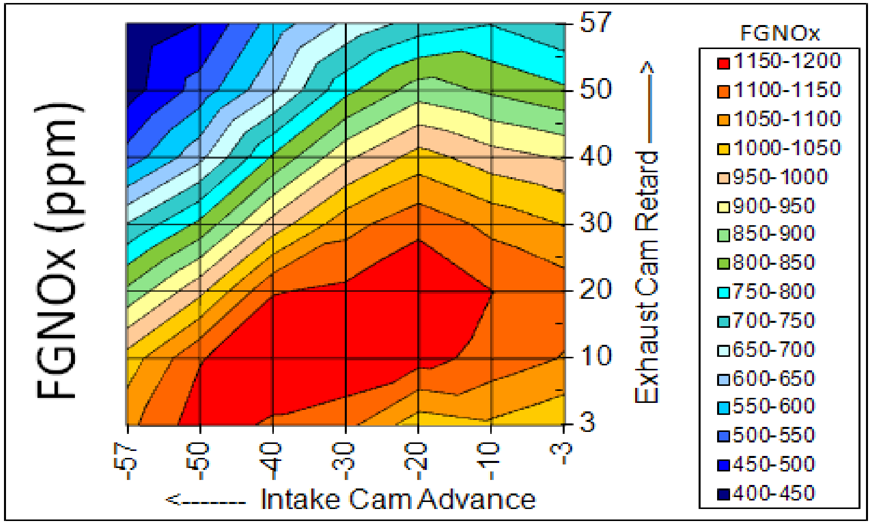
- Displacement / Cylinder = 565 cm3
- Bore & Stroke = 87.5 & 94.0 mm
- Compression Ratio = 11.5:1
- Bore Spacing = 96.0 mm
- Bore Bridge = 8.5 mm
- Deck Height = 222 mm

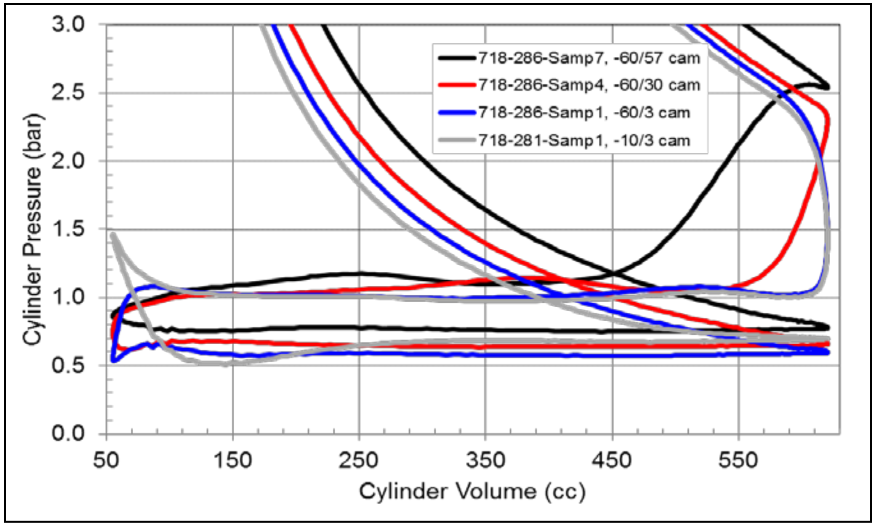
- Transverse central DI + ignition w/ intake biased multi-hole injector
- Advanced boosting system + active wastegate
- Low pressure, cooled EGR system
- Composite intake manifold w/ integrated air-water charge air cooler assembly
- Split, parallel, cross-flow cooling with integrated exhaust manifold
- Integrated variable displacement oil pump / balance shaft module
- Compact RFF valvetrain w/ 12 mm HLA
- Roller bearing cam journals on front, all other locations conventional
- Electric tiVCT

- MCE Evaluation on Dynamometer – Electric tiVCT Cam Timing 2000 RPM / 5 bar BMEP

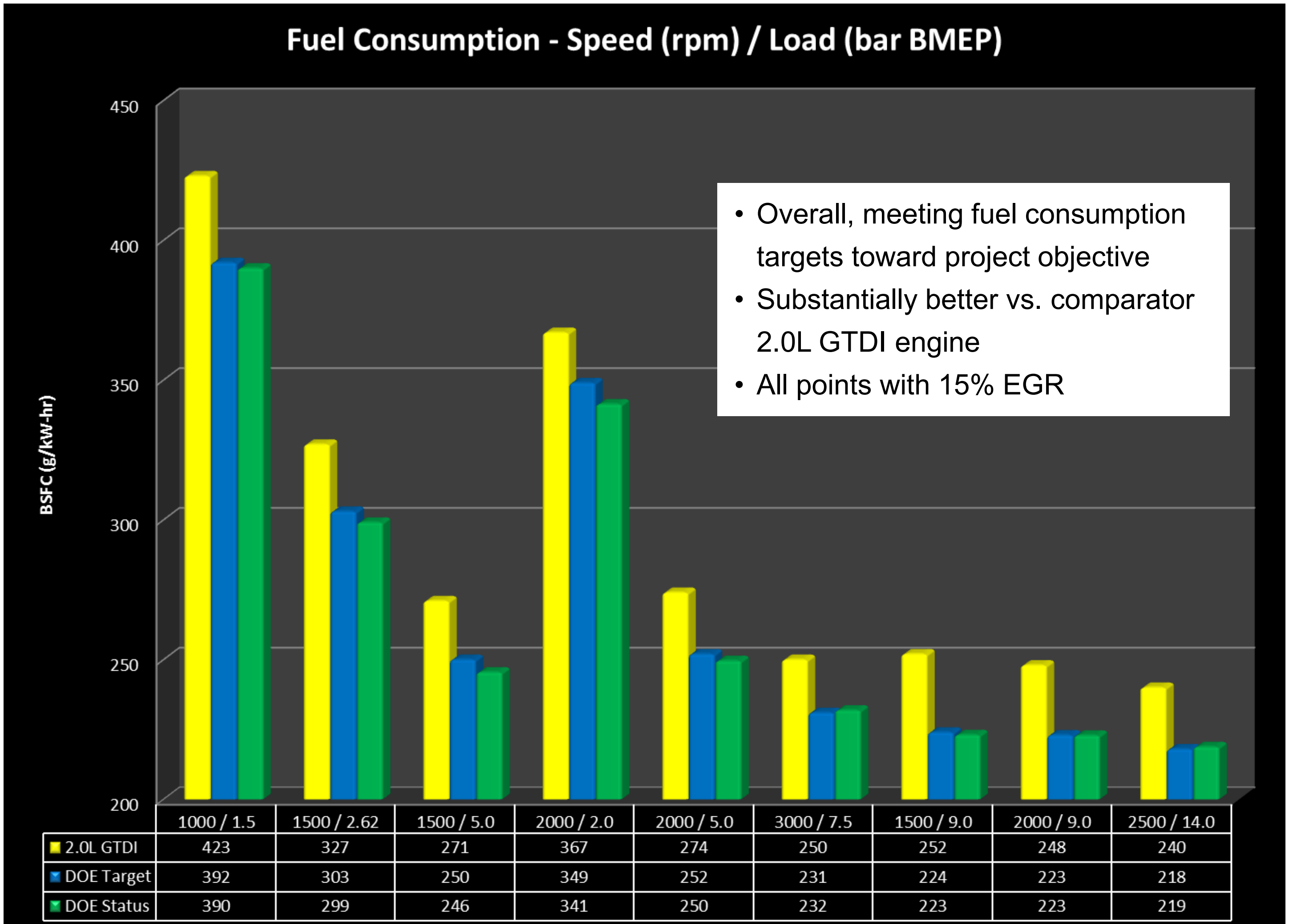






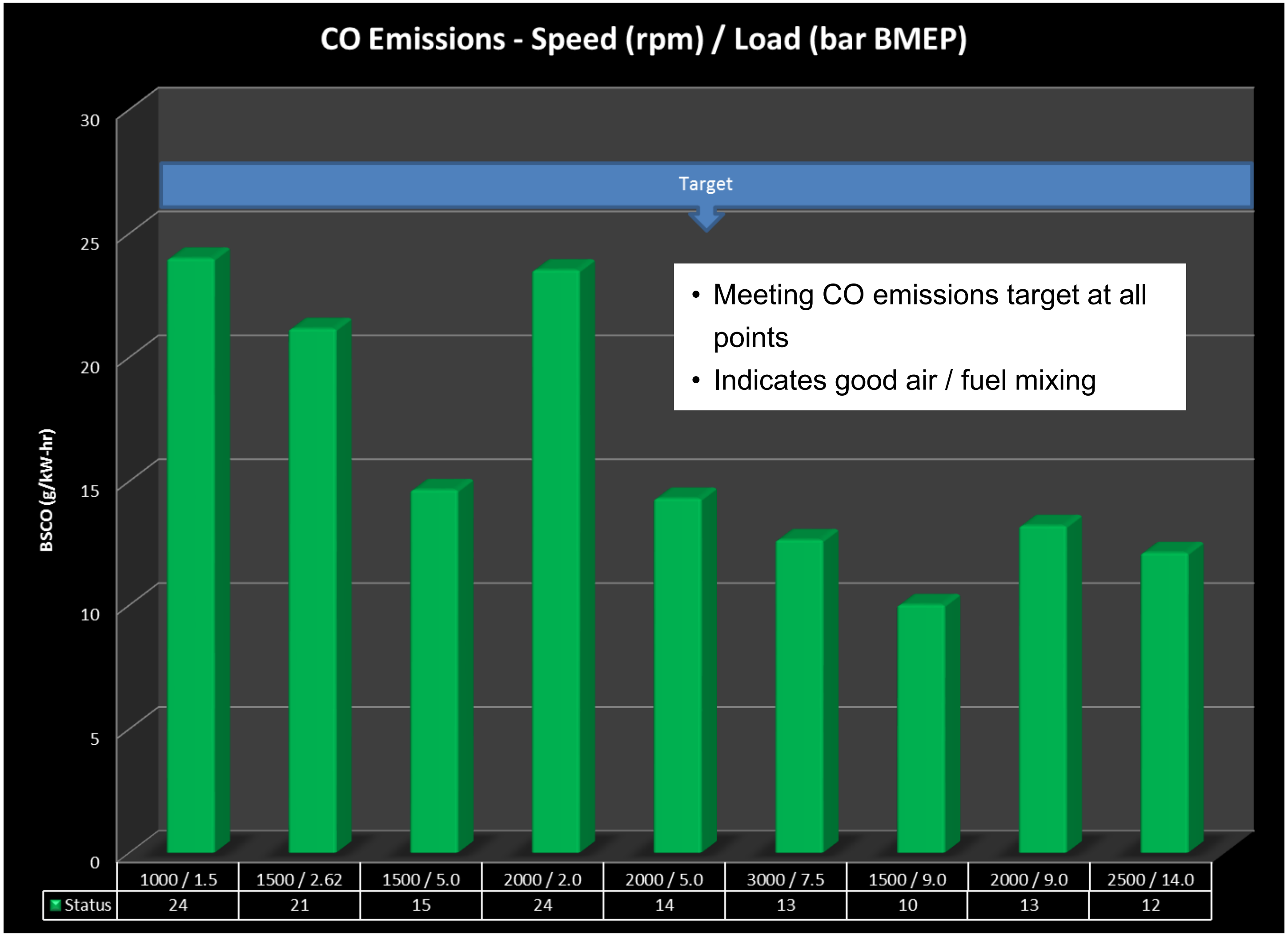


- MCE Evaluation on Dynamometer – Part Load Fuel Consumption



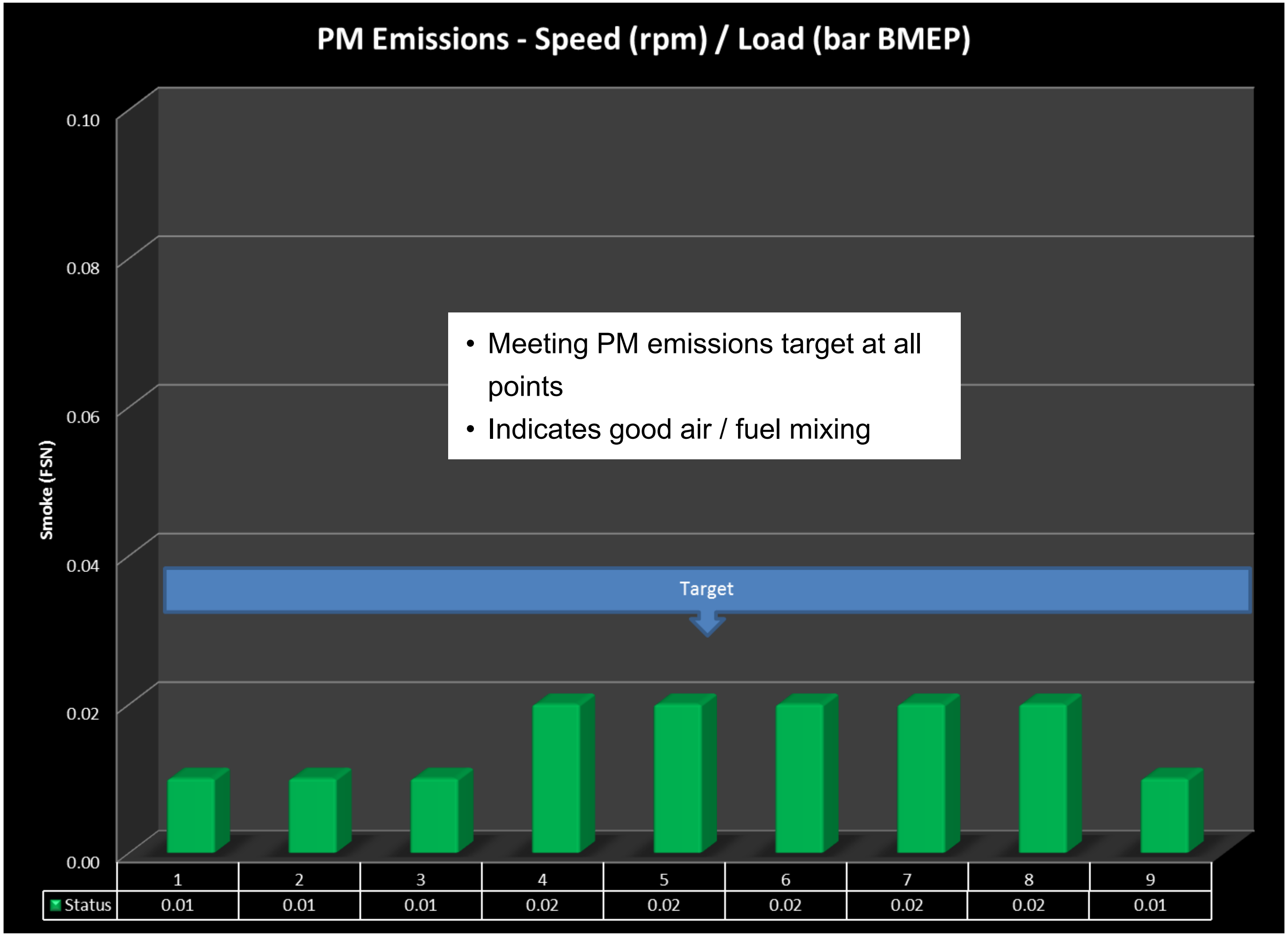
	1000 / 1.5	1500 / 2.62	1500 / 5.0	2000 / 2.0	2000 / 5.0	3000 / 7.5	1500 / 9.0	2000 / 9.0	2500 / 14.0
2.0L GTDI	423	327	271	367	274	250	252	248	240
DOE Target	392	303	250	349	252	231	224	223	218
DOE Status	390	299	246	341	250	232	223	223	219

- MCE Evaluation on Dynamometer – Part Load CO Emissions

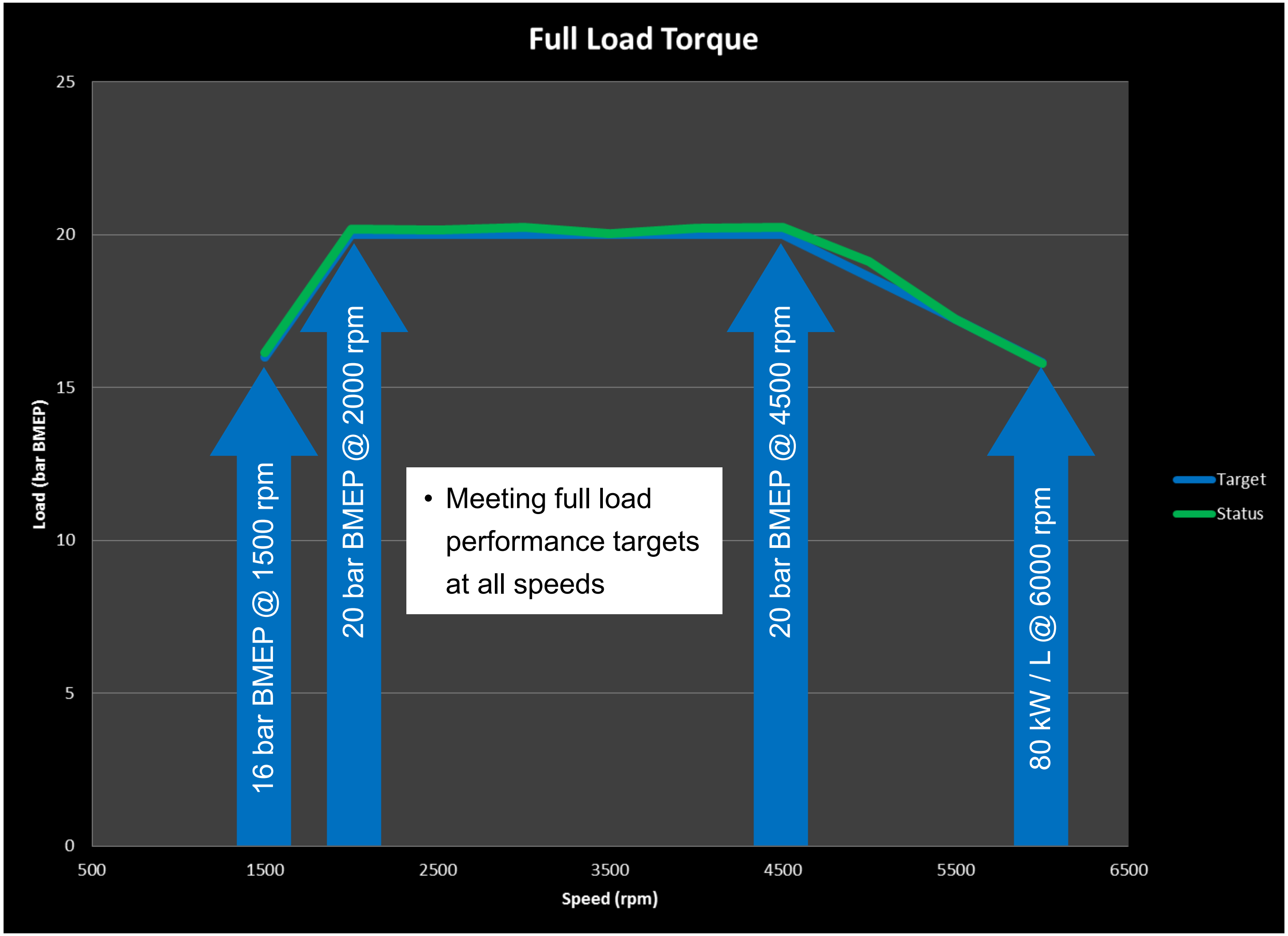


Accomplishments

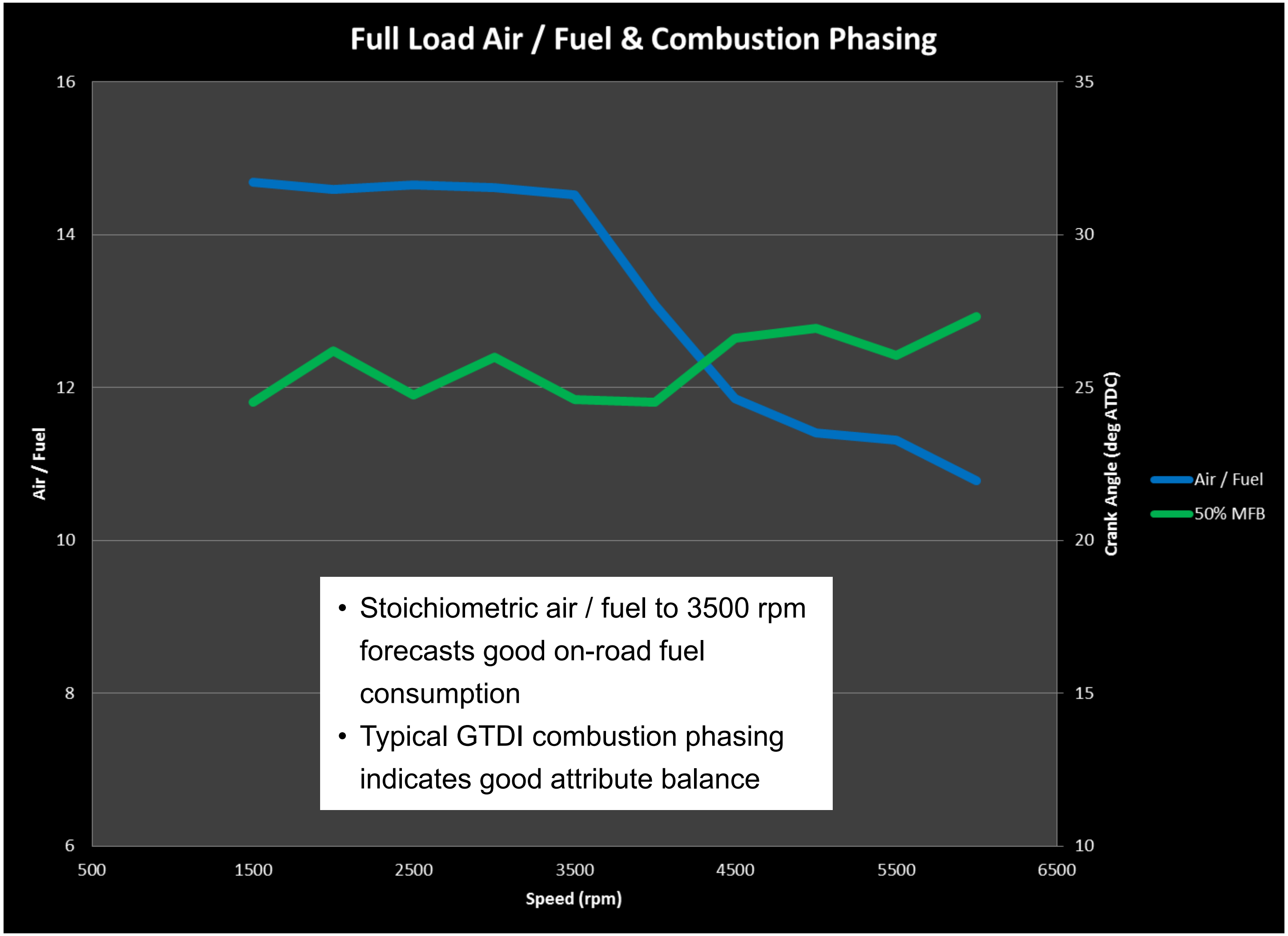
- MCE Evaluation on Dynamometer – Part Load PM Emissions



- MCE Evaluation on Dynamometer – Full Load Performance

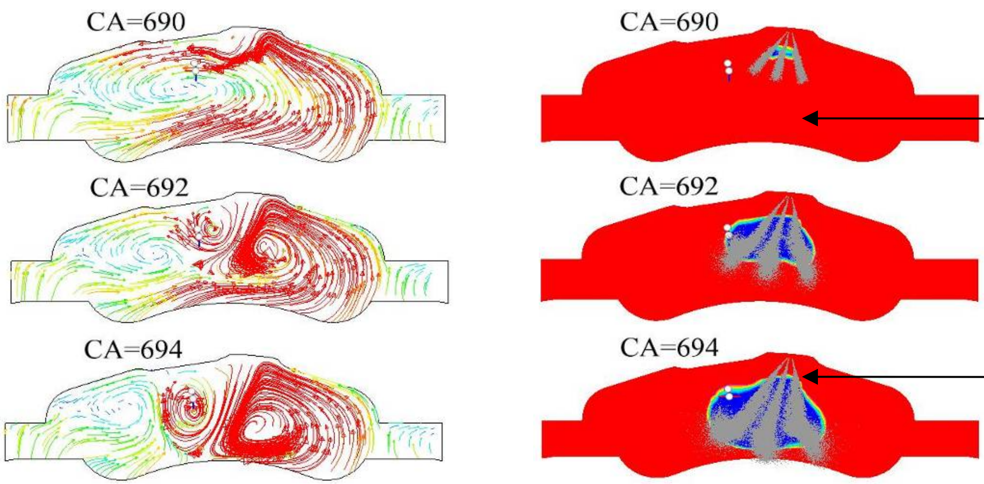


- MCE Evaluation on Dynamometer – Full Load Performance



- MCE Evaluation on Dynamometer – “Micro” Stratified Charge

Air Flow & Air / Fuel Spatial
& Temporal Evolution



“Micro” Stratified Charge

=

- Overall Lean Homogeneous
- Early Primary Injection
- Air / Fuel ~ 20-30:1

+

- Locally Rich Stratified
- Late Secondary Injection
- “Micro” Second Pulsewidth

- Advantages of “micro” stratified charge capability

✓ Good fuel economy
✓ Low NOx emissions
✓ Low PM emissions

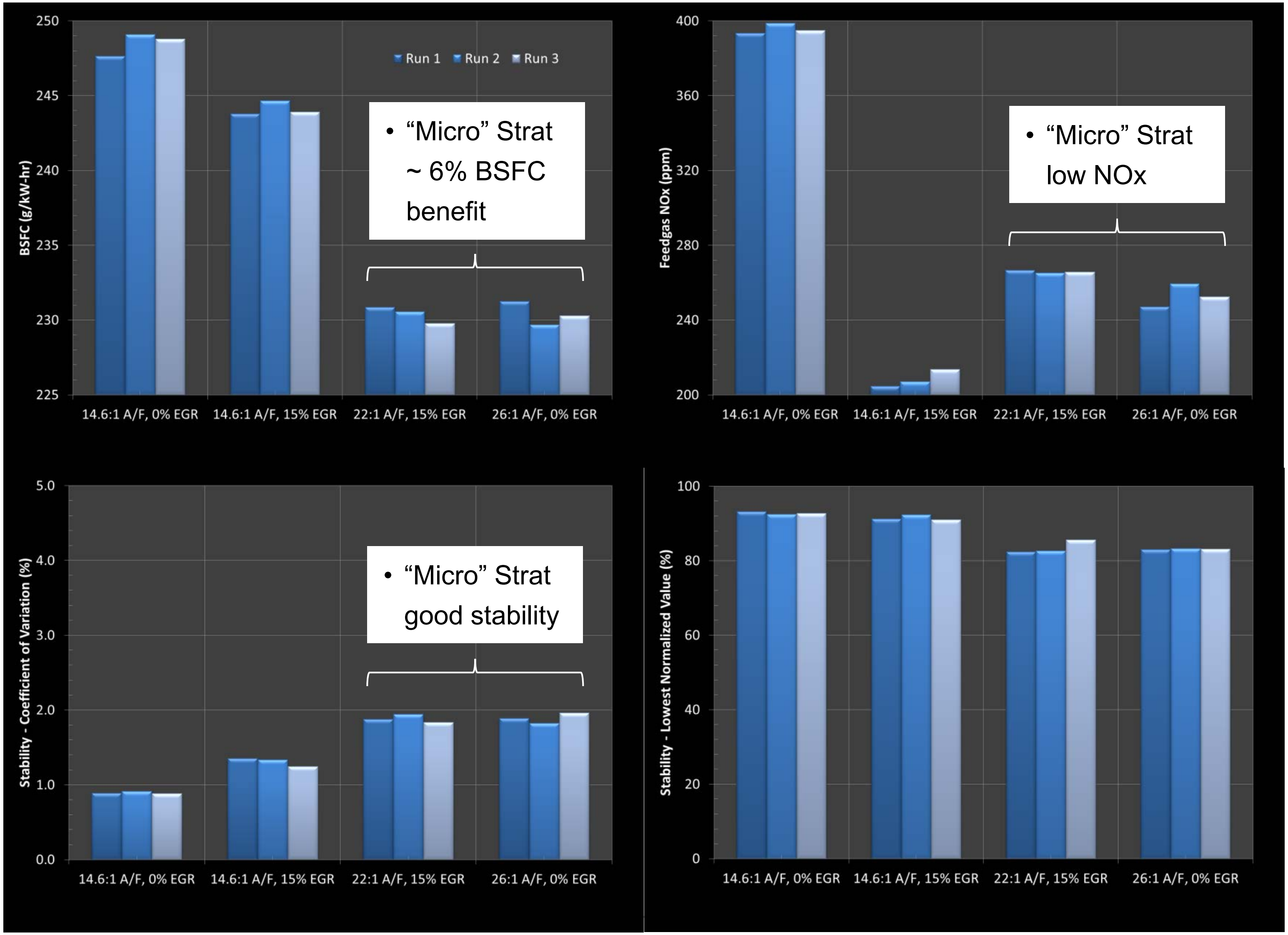
✓ Practical controls
✓ Acceptable NVH
✓ Good stability

✓ Extends lean combustion capability to region of good aftertreatment efficiency, potentially enabling an LNT / SCR or passive SCR system

Accomplishments

Research and Advanced Engineering

- MCE Evaluation on Dynamometer – "Micro" Stratified Charge 1500 RPM / 5.0 bar BMEP



Accomplishments

Research and Advanced Engineering

- MCE Evaluation on Dynamometer – Cold Start Emissions
  - ✓ Substantially completed transient emissions verification testing, including steady state cold fluids development and transient cold start development
  - ✓ Received concurrence on transitioning Tier 2 Bin 2 to Tier 3 SULEV30 emissions

Tailpipe Standards	Tier 2 Bin 2	Tier 3 SULEV30
NMOG	10 mg / mi	--
NOx	20 mg / mi	--
NMOG + NOx	--	30 mg / mi
PM	10 mg / mi	3 mg / mi

  - ✓ Meeting 20°C Cold Start Feedgas Targets – Derived From Tailpipe Standards

Cold Start Attribute	Units	Target[1]	Status
0-20s Cumulative FGHC + FGNOx	mg	< 227	224
0-20s Cumulative Particulate Mass (PM)	mg	< 3.0	1.3
5-15s CSER stability (RMS_SDIMEP)	bar	< 0.350	0.375

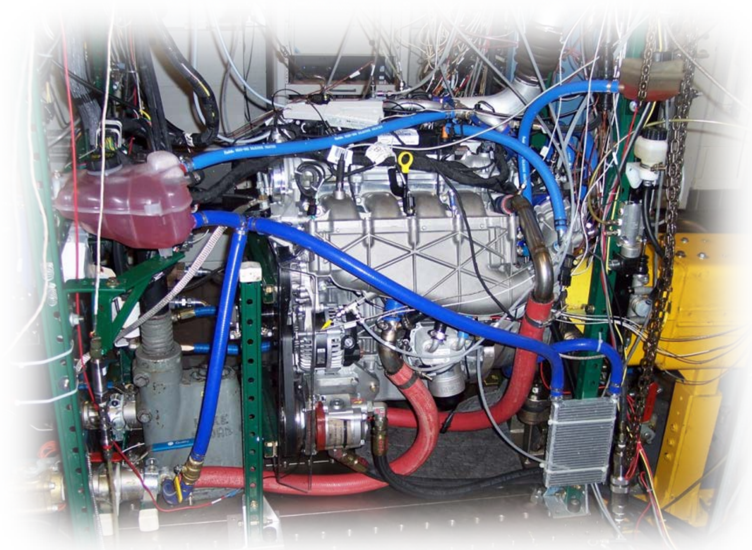
[1] Evaluated at a CSER heat flux that achieves ~350°C catalyst mid-bed @ 20 seconds after engine start

Accomplishments

- MCE Evaluation on Dynamometer – Mapping

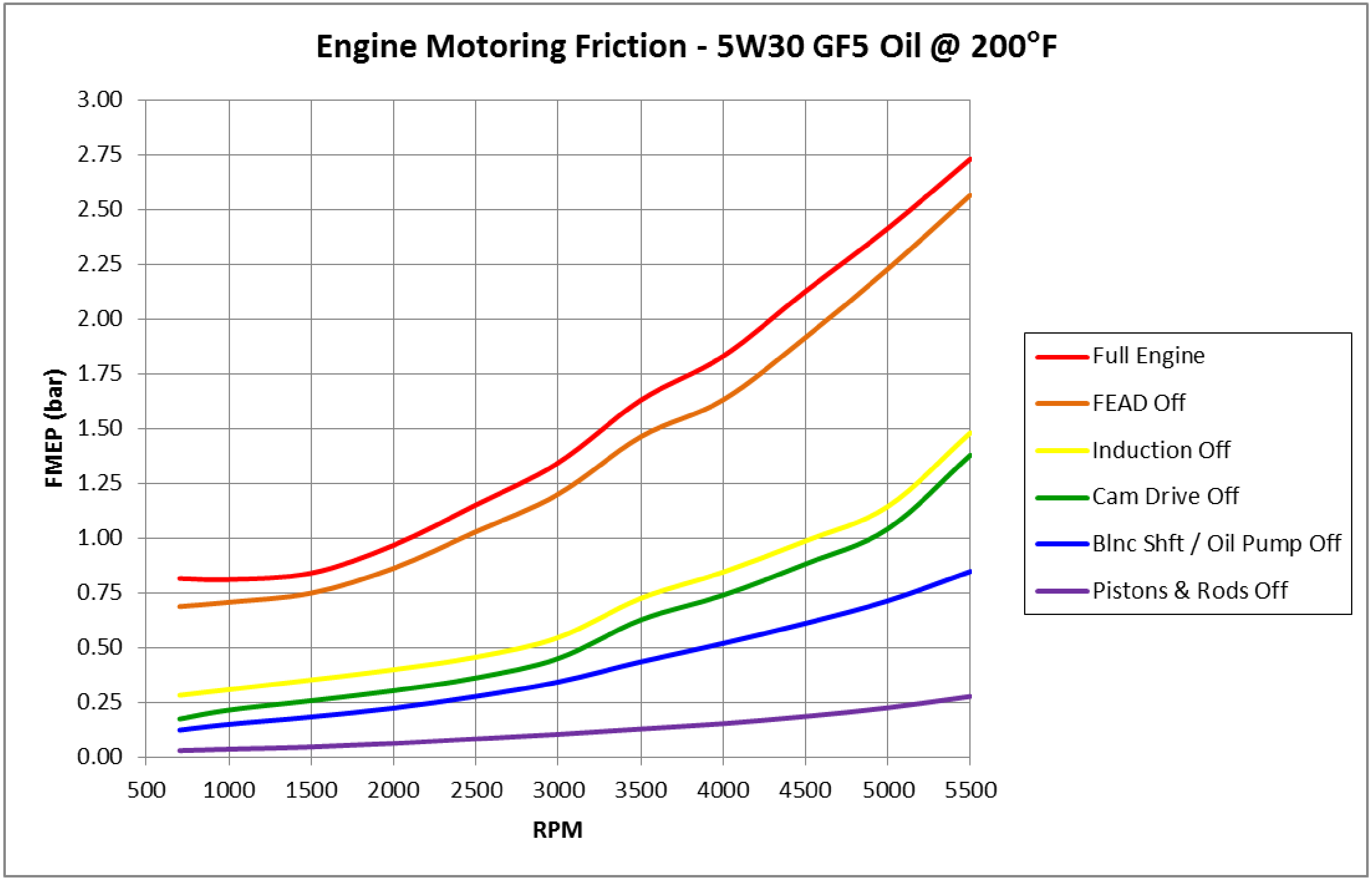
  - ✓ Substantially progressed engine mapping in support of vehicle calibration, including effectively utilizing "auto test" control for autonomous engine mapping

    - ✓ Electric tiVCT Cam Timing Optimization
    - ✓ DI Fuel Injection Timing Optimization
    - ✓ DI Fuel Rail Pressure Optimization
    - ✓ Naturally-Aspirated Air Charge – Throttle Sweeps
    - ✓ Boosted Air Charge – Scroll / Wastegate Control Sweeps
    - ✓ Full Load Performance – BLD / MBT Spark Sweeps
    - ✓ Preliminary "Auto" Calibration



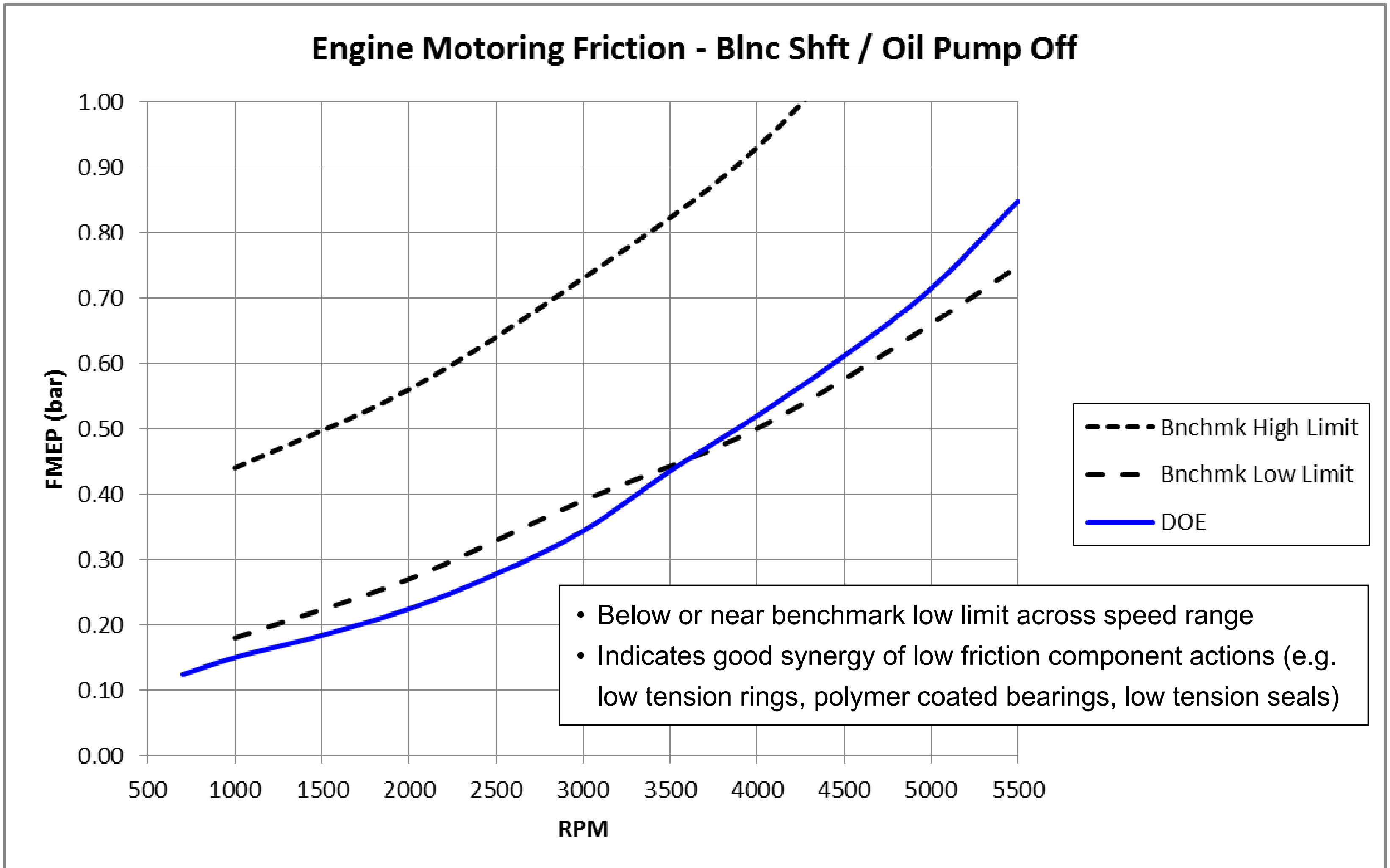
  - ✓ Initiated mapping validation testing and additional detailed mapping factorials as required to ensure accuracy

- MCE Evaluation on Dynamometer – Friction Testing



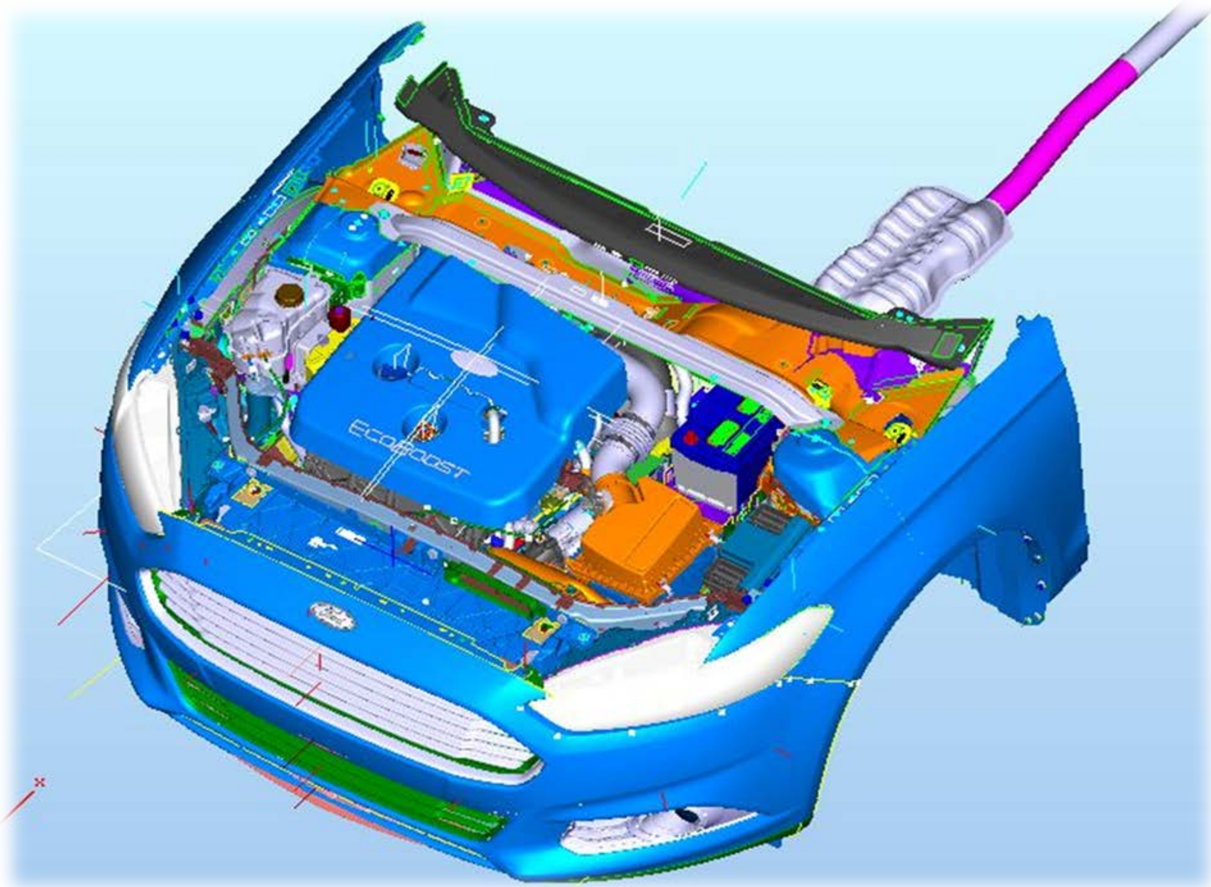
Accomplishments

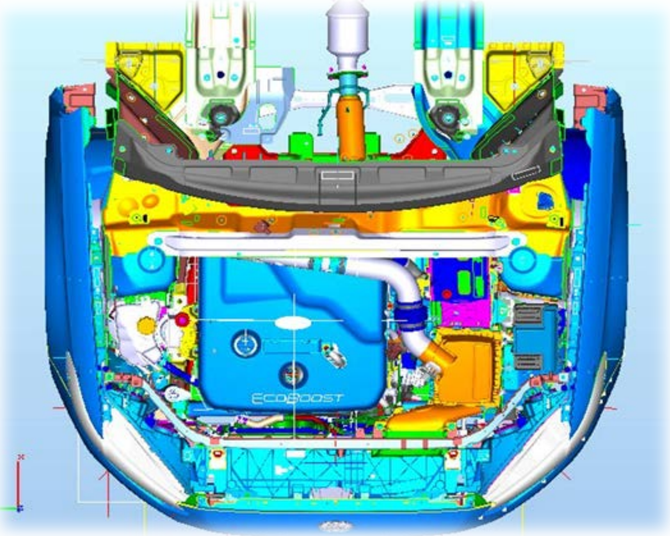
- MCE Evaluation on Dynamometer – Friction Testing



Accomplishments

- Vehicle Build and Development – Engine As Installed In 2013 Fusion





- Vehicle Build and Development – Engine As Installed In 2013 Fusion

Accomplishments

Ford Research and Advanced Engineering

- Vehicle Build and Development – Engine As Installed In 2013 Fusion

Vehicle #1 Completed, Starting Calibration Development

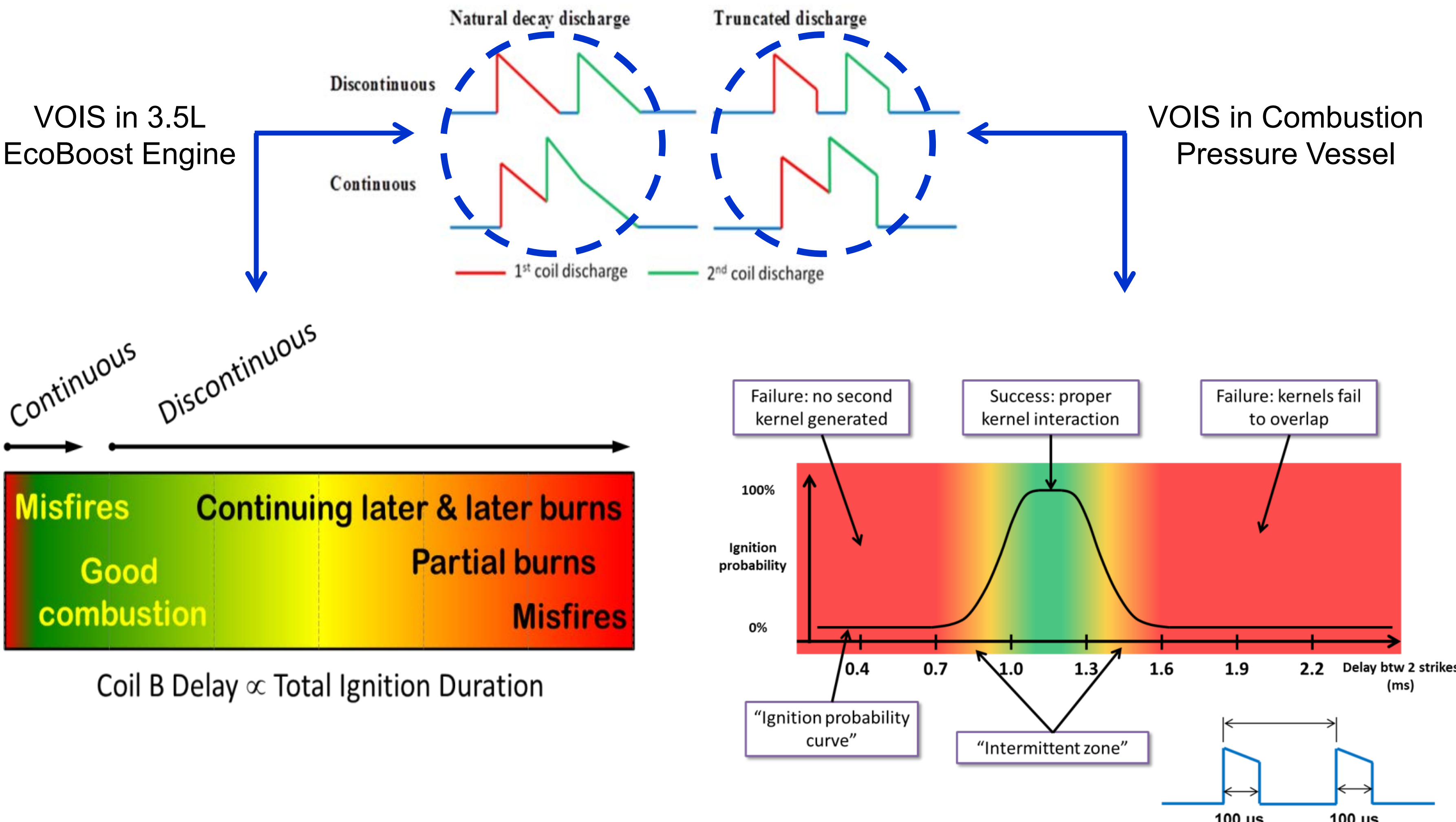
Vehicles #2 – 4 Build In Progress … Online Soon

Collaboration

- Combustion Research (MTU)
  - ✓ Completed all six research tasks focused on expansion of dilute engine operating limits
  - ✓ Continued three research tasks with Ford funding, using the pressure vessel and two EcoBoost engines
    1) Advanced Ignition & Flame Kernel Development – Published & presented SAE 2013-01-1627
    2) Advanced Ignition – Impact on Dilute Combustion – Published & presented SAE 2013-01-1630
    3) Air / Fuel Mixing via PLIF for GDI – Completed test plan in pressure vessel; report in progress
    4) Combustion Sensing & Control – Demonstrated closed loop control of combustion phasing & stability; report in progress
    5) Advanced Knock Detection & Control – Completed development of stochastic knock algorithms; SAE paper in progress
    6) In-Cylinder Temps & Heat Flux – Completed test plan in EcoBoost engine; published results in Ph.D. dissertation.

Collaboration

- Optimization of VOIS discharge pattern for successful flame initiation and propagation yields similar results in engine and pressure vessel

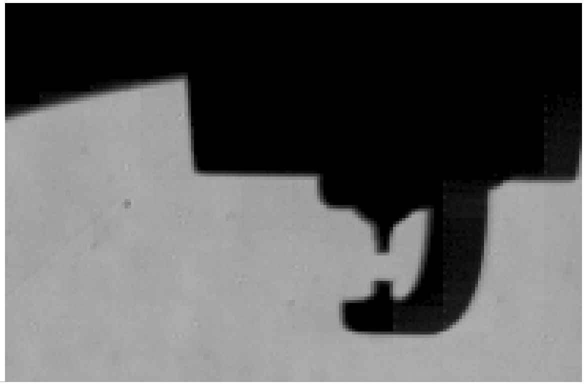


Collaboration

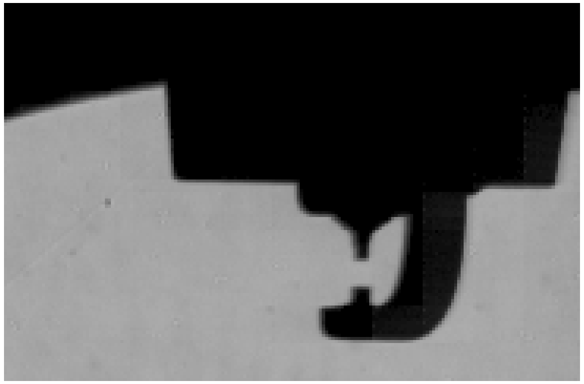
Research and Advanced Engineering

- Optimization of VOIS discharge pattern for successful flame initiation and propagation
- Conditions
  - Combustion vessel
  - Double fine wire plug
  - 1.2 mm gap
  - 10% EGR, $\lambda = 1.6$
  - 150 deg C, ~ 4 bar
  - 2 – 3 m/s cross flow
- Multiple flame kernels merge for success!

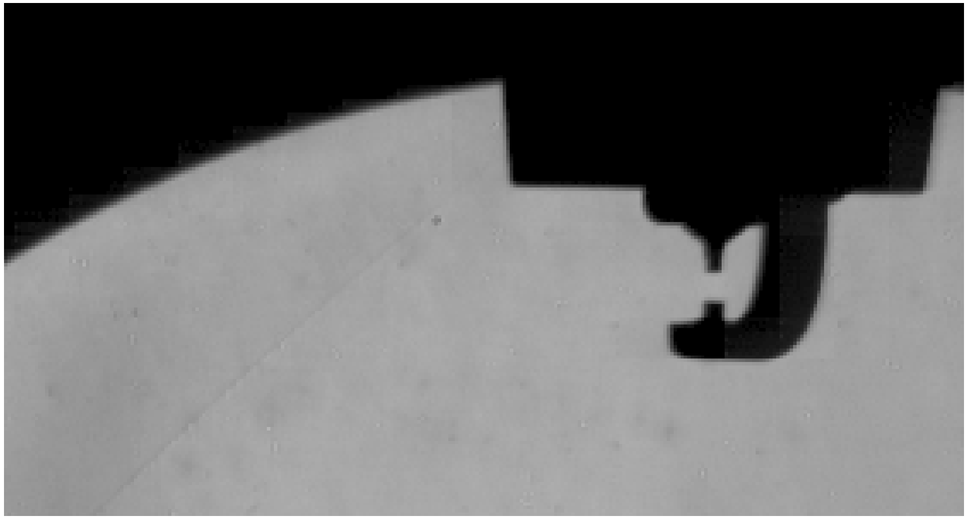
2 Strikes @ 0.7 ms Delay = Failed Ignition



2 Strikes @ 1.6 ms Delay = Failed Ignition



2 Strikes @ 1.0 ms Delay = Successful Ignition!



Previous Reviewer Comments

Research and Advanced Engineering

- "On time to revised timeline (revised architecture)"
  - Original architecture was 1.8L I4 / 25 bar BMEP; during concept evaluation, revised architecture to 2.3L I4 / 20 bar BMEP
- "Vehicle integration will be challenging in 12 months"
  - Project end 12/31/14; likely to request no cost extension to 09/30/15
- "Stopped work on lean aftertreatment"
  - Given the DeSOx challenges of a TWC + LNT / SCR system, and the uncertainty of a TWC + passive SCR system, received concurrence on lean aftertreatment transitioning to stoichiometric at the vehicle level.
  - Continued lean combustion "Micro" Stratified Charge development at the dyno level (results presented herein); lean aftertreatment challenges persist.

Future Work

- Budget Period 4 – Vehicle Development 01/01/2014 – 09/30/2015
  - Vehicle demonstrates greater than 25% weighted city / highway fuel economy improvement and Tier 3 SULEV30 emissions on FTP-75 test cycle

Summary

Research and Advanced Engineering

- The project will demonstrate a 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics, while meeting Tier 3 SULEV30 emissions on FTP-75 cycle.
- Ford Motor Company has engineered a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, assembled a cross-functional team of subject matter experts, and progressed the project through the concept analysis, design, development, and evaluation tasks with material accomplishments to date.
- The outlook for 2014 is stable, with accomplishments anticipated to track the original scope of work and planned tasks, with the exception of milestone "Vehicle build, instrumented, and development work started" deferred from 12/31/2013 to 02/14/2014.