Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development

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Ford Research and Advanced Engineering

05/17/2013

Project ID: ACE065

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Overview

- Timeline
  - Project Start 10/01/2010
  - Project End 12/31/2014
  - Completed 55%

- Total Project Funding
  - DOE Share $15,000,000.
  - Ford Share $15,000,000.
  - Funding in FY2012 $ 9,330,648.
  - Funding in FY2013 $ 4,911,758.

- Barriers
  - Gasoline Engine Thermal Efficiency
  - Gasoline Engine Emissions
  - Gasoline Engine Systems Integration

- Partners
  - Lead Ford Motor Company
  - Support Michigan Technological University (MTU)

Background

- 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

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- 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 2 Bin 2 emissions on FTP-75 cycle.

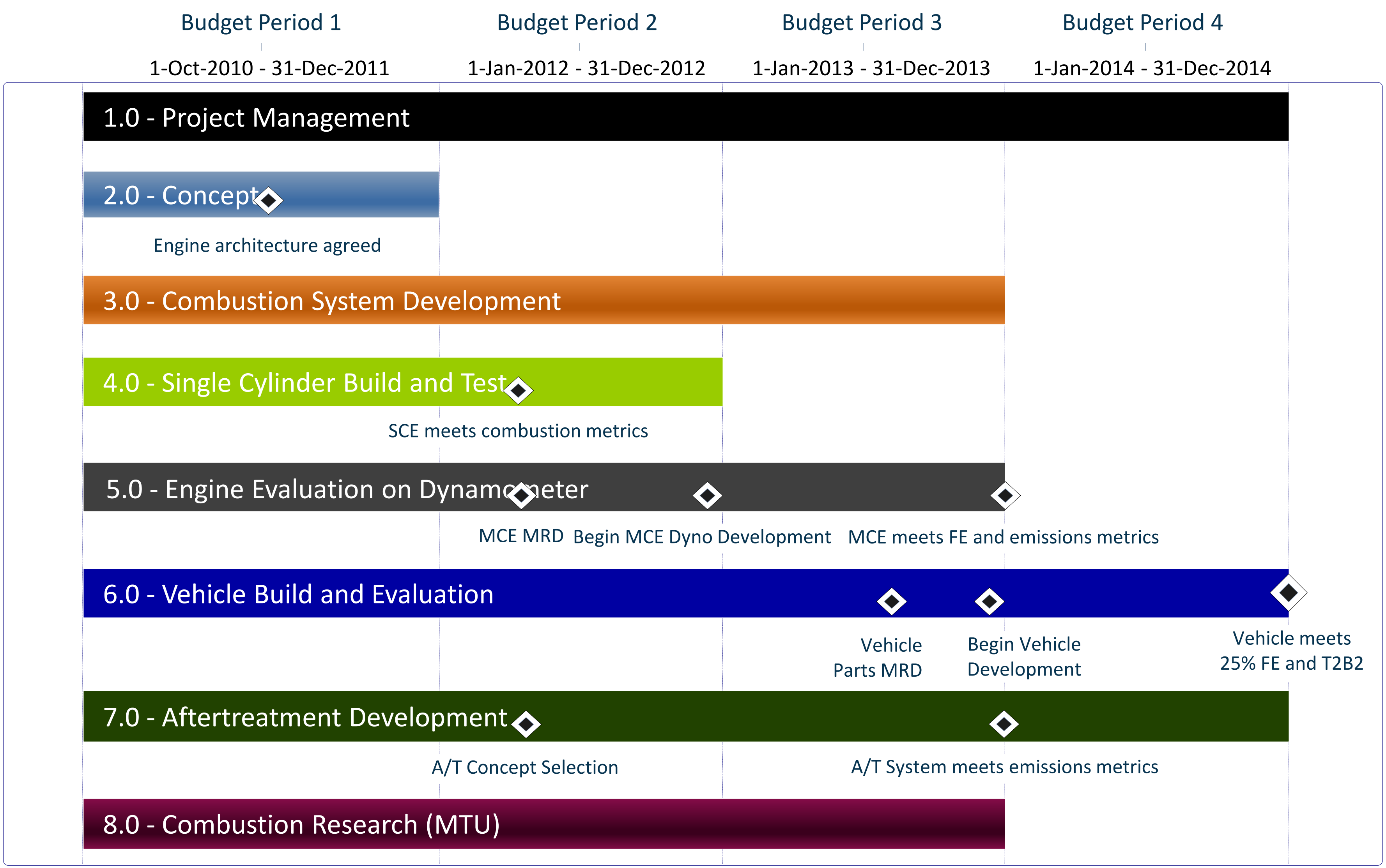
- MTU Objectives:
  - Support Ford Motor Company in the research and development of advanced ignition concepts and systems to expand the dilute / lean engine operating limits.

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



Project Assumptions

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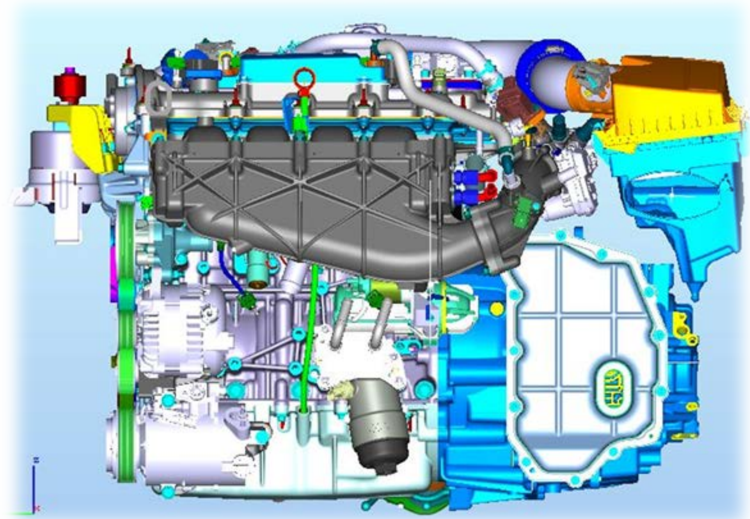
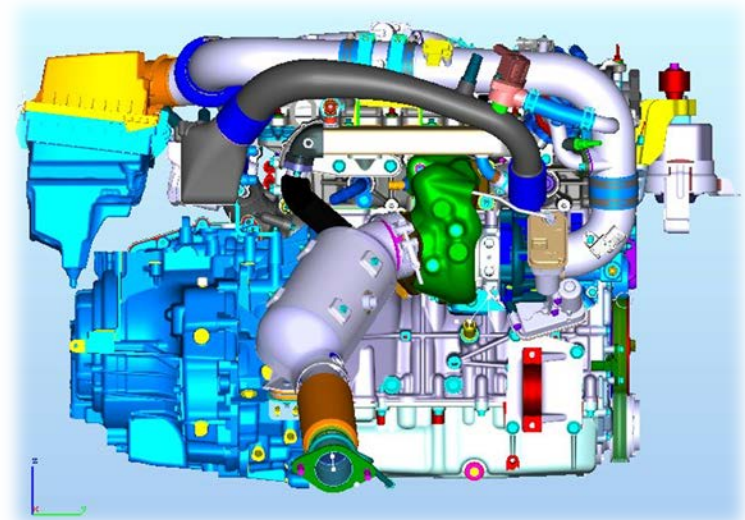
- Attribute Assumptions

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





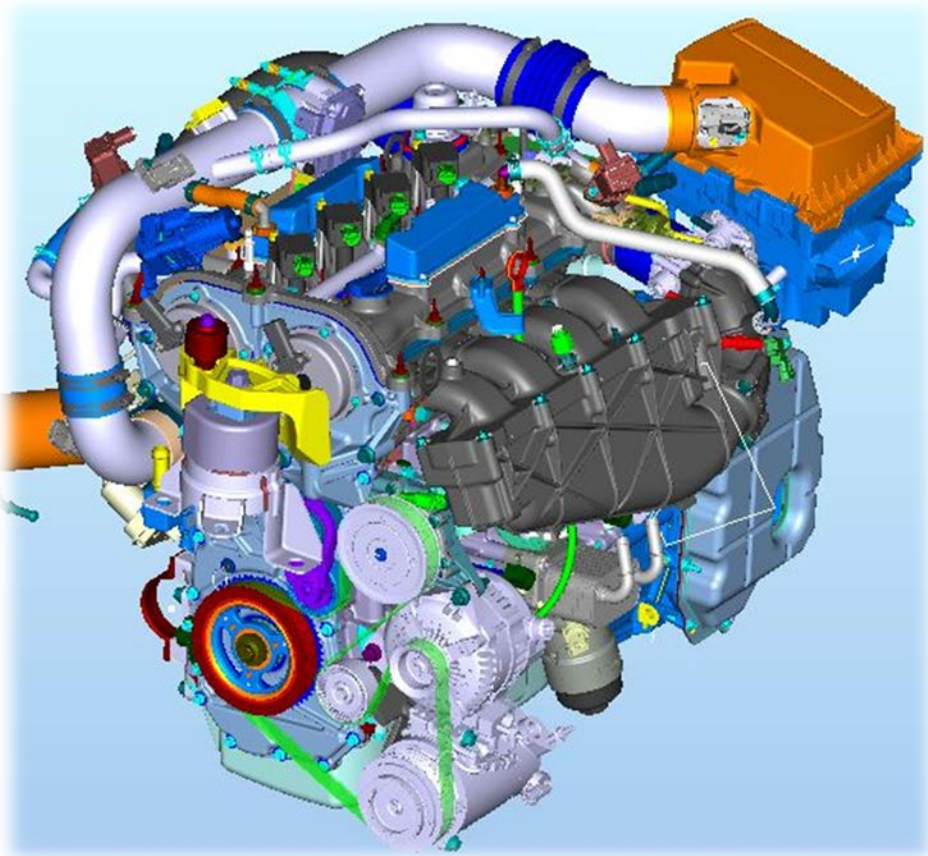
Project Assumptions

Research and Advanced Engineering

- Systems Assumptions
  - Transverse central DI + ignition w/ intake biased multi-hole injector
  - 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

  - 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



Accomplishments

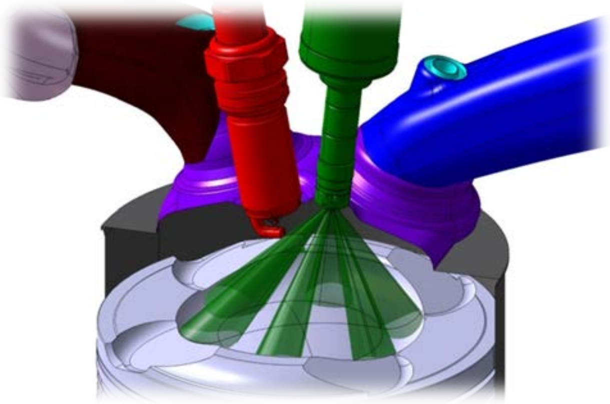
Research and Advanced Engineering

- Combustion System Development

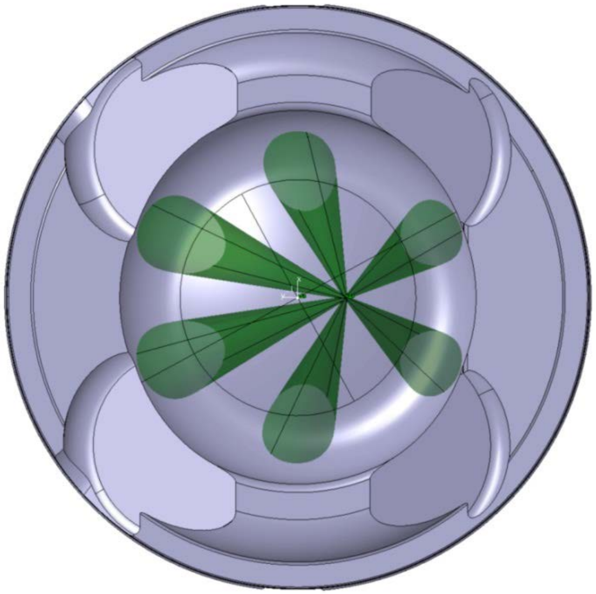
  ✓ Completed port, chamber, injector, and piston specifications to enable combustion system iteration option (i.e. risk mitigation) during the multi-cylinder engine (MCE) evaluation on dynamometer phase of the project.

  - Objective optimization metrics included:
    - Spatial & temporal evolution of air flow, tumble ratio, turbulence intensity
    - Spatial & temporal evolution of air / fuel, cylinder bore & piston crown fuel impingement & wetting
    - Homogeneous charge, part-load & full-load, balanced with stratified charge, part-load operating conditions

Combustion System – Section View



Combustion System – Plan View

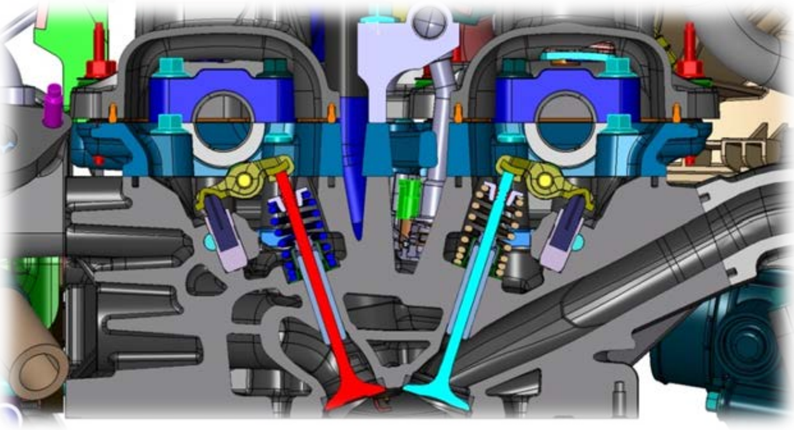


Accomplishments

Research and Advanced Engineering

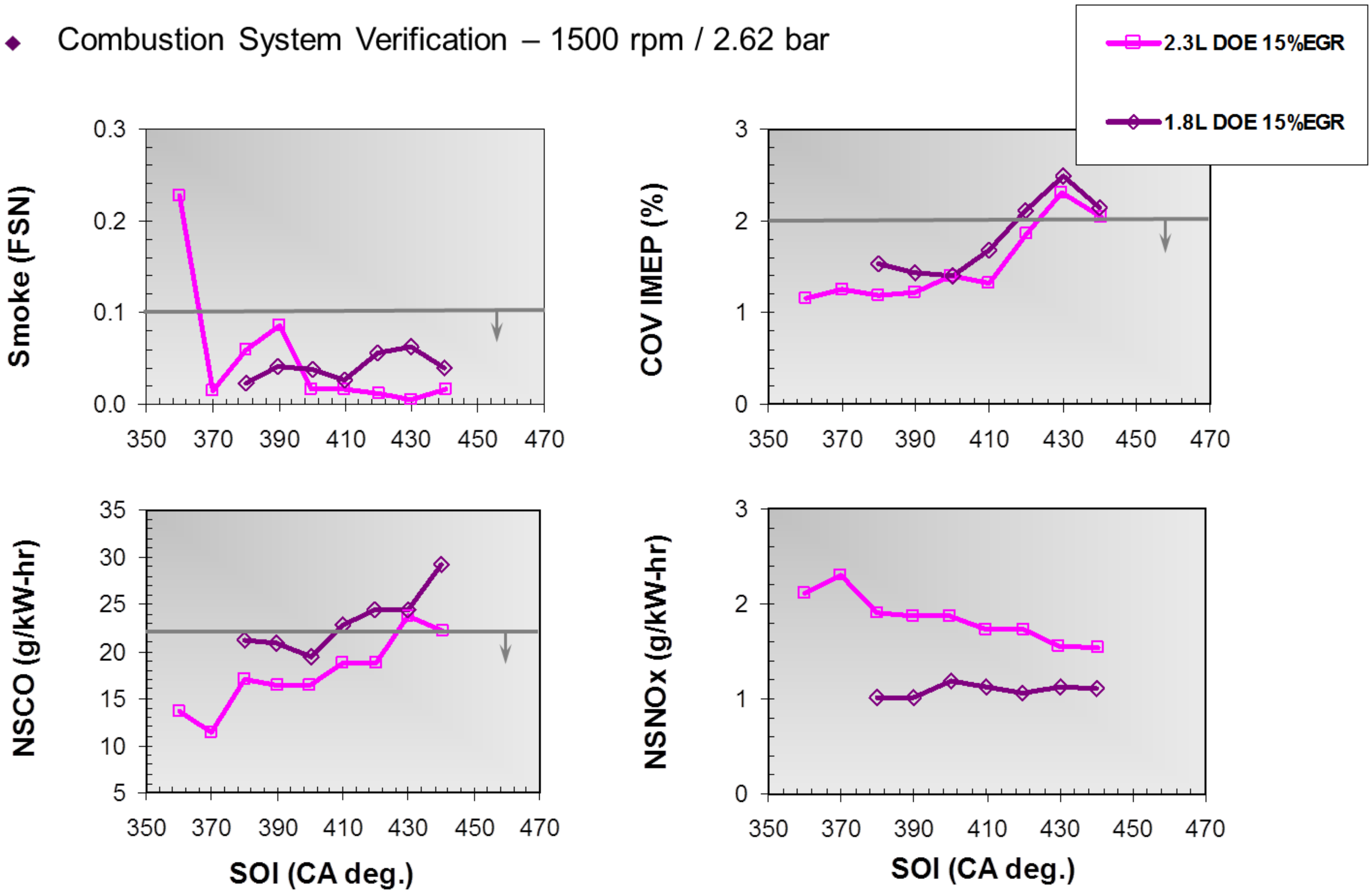
- Single Cylinder Build and Test
  - ✓ Completed installation and commissioning of new 2.3L SCE.
  - ✓ Initiated combustion system verification testing to ensure combustion system meets target metrics, including fuel consumption, stability, and emissions.
  - ✓ Completed part-load, lean and stoichiometric, air-fuel ratio sweeps, injection timing sweeps, cooled EGR sweeps, and cam timing sweeps.
  - ✓ **Testing to date indicates combustion system satisfies target metrics.**

Multi-Cylinder Head – Section View



SCE Head – Rapid Prototype (~1 Month)

- Single Cylinder Build and Test
  - Combustion System Verification – 1500 rpm / 2.62 bar



Accomplishments

Research and Advanced Engineering

- Engine Design / Procure / Build
  - ✓ Completed procurement process in support of May 1, 2012 multi-cylinder engine material required date (MCE MRD); completed bill of material, component tooling and piece costs, and supplier request for quote / sourcing process with Ford Prototype Purchasing.
  - ✓ Completed manufacturing process reviews (e.g. cylinder block casting & machining, cylinder head casting & machining, cover castings & machining).
  - ✓ Completed assembly process reviews, assembly illustrations, and assembly aids.
  - ✓ **Completed MCE build and firing of 1st, 2nd, 3rd, and 4th of 12 engines; initiated MCE evaluation on dynamometer phase of the project .**
  - Remainder of 12 engines to be built following combustion system / mechanical verification.

Accomplishments

Research and Advanced Engineering

Accomplishments

2.3L MiGTDI Pre-X0 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

Accomplishments

Research and Advanced Engineering

 #1 – Combustion System / Mechanical Verification

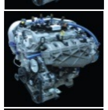
 #2 – Cold Start Emissions Development

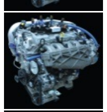
 #3 – Steady State Mapping

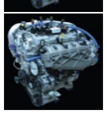
 #4 – Mechanical Friction Study ⇨ NVH Study

Phase 1 Build
3-4Q'12

 #5 – Performance Development

 #6 – Thermal Management Studies

 #7 – Mechanical Development Studies

 #8 – Spare ☺

Phase 2 Build
2Q'13

Phase 3 Build
3Q'13

 #9

 #10

 #11

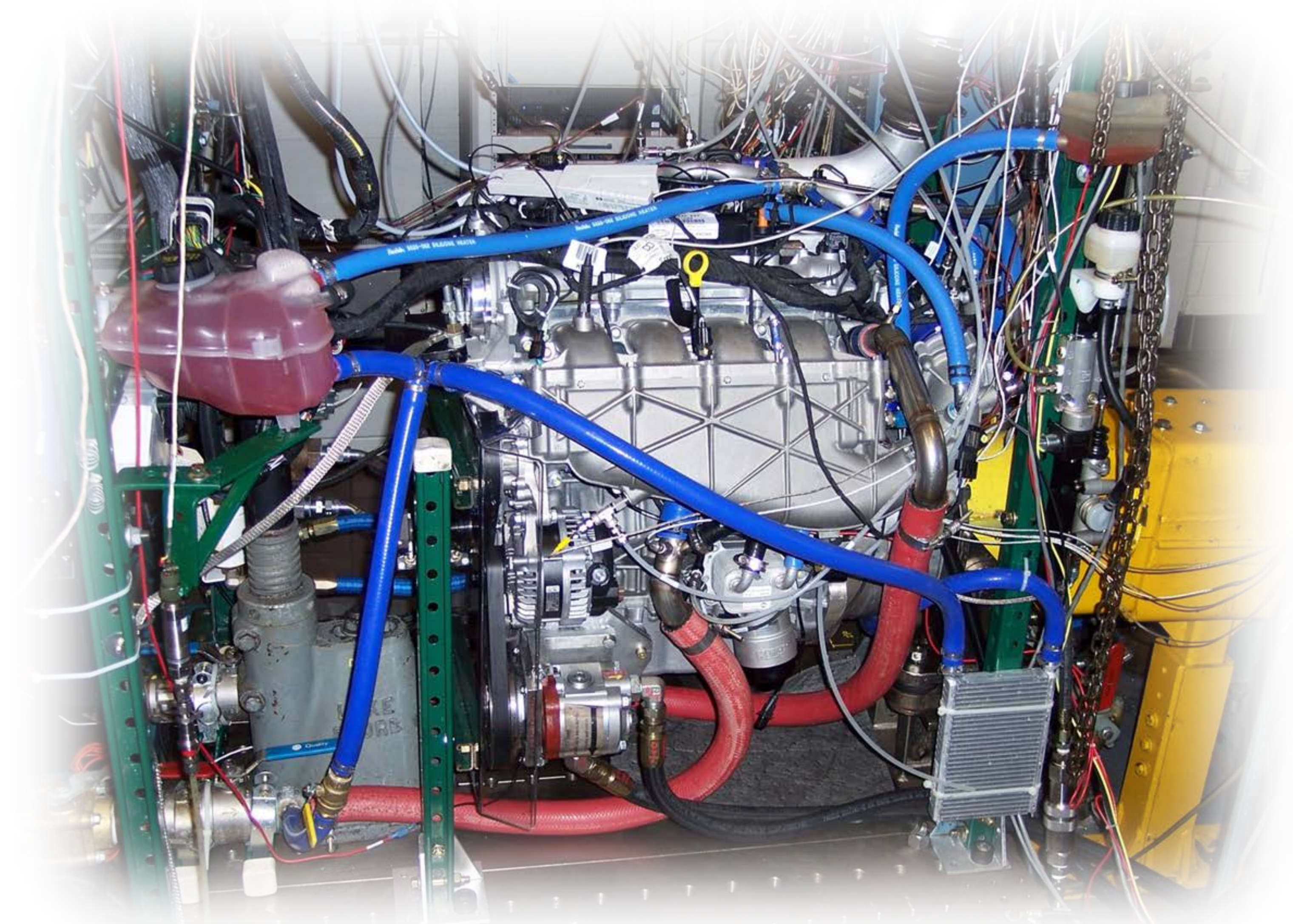
 #12

Calibration → Vehicles (4)

Accomplishments

Research and Advanced Engineering

- MCE Evaluation on Dynamometer – As Installed @ Research & Innovation Center



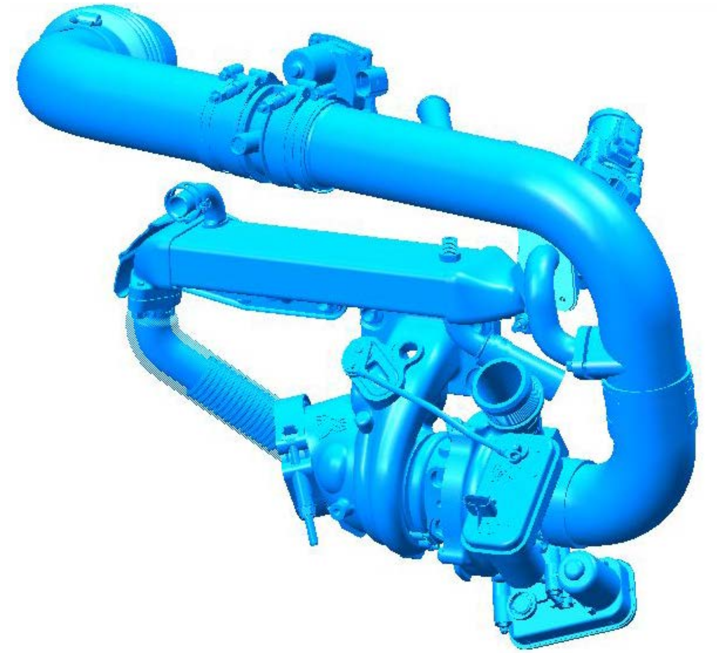
Accomplishments

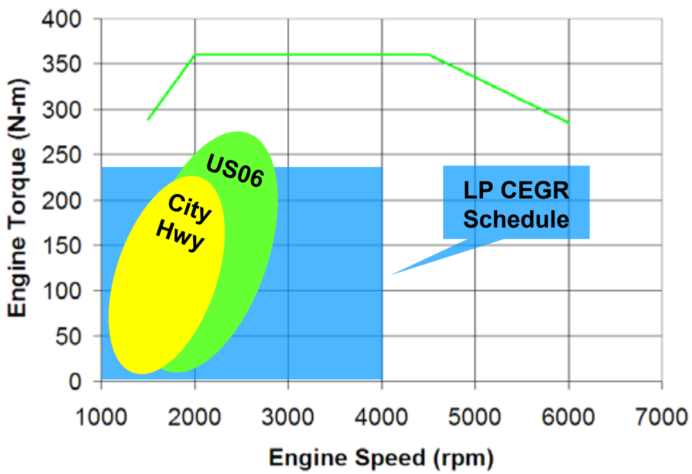
Research and Advanced Engineering

Low pressure, cooled EGR system

- Advantages
  - Improved fuel economy via reduced pumping & heat losses at lower speed & loads
  - Improved fuel economy via reduced knocking tendancy & enrichment at higher speed & loads
  - Improved emissions via reduced enrichment at higher speed & loads

- Challenges
  - Transport delay during speed & load transients
  - Mechanical robustness of charge air cooler and compressor due to EGR exposure
  - Additional controls requirements for EGR valve and throttle

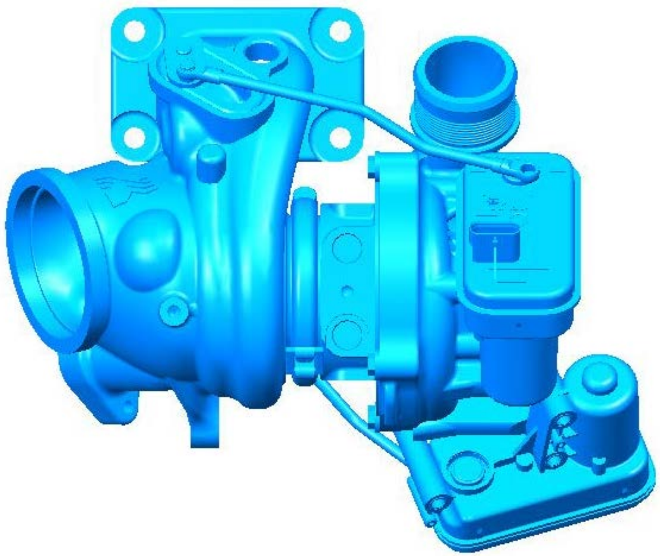


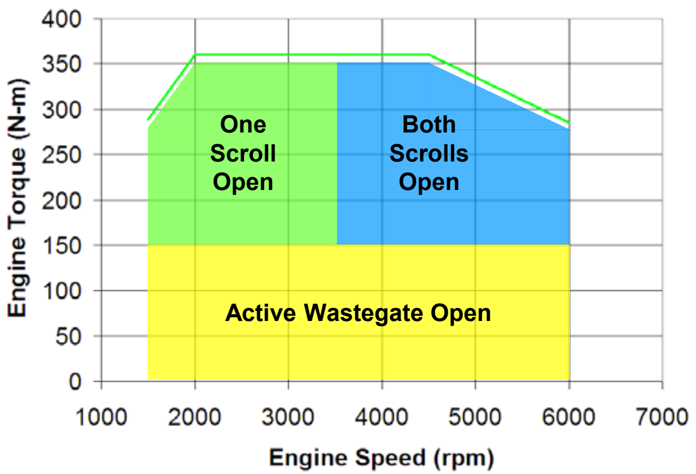


Accomplishments

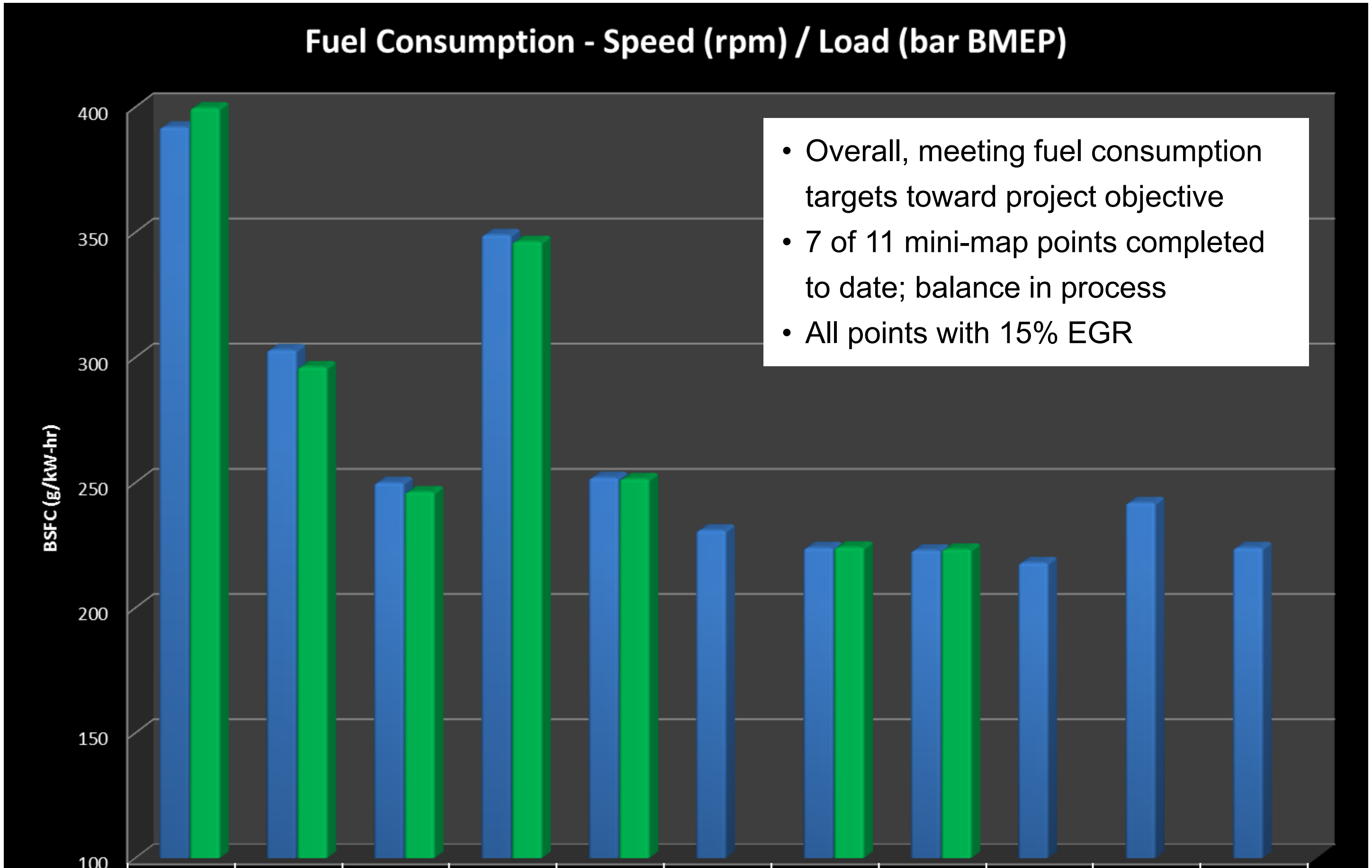
Twin scroll turbocharger w/ scroll control valve + active wastegate

- Advantages
  - Combines benefits of a sequential turbo system with simplicity of a single turbo system
  - Good low speed torque & transient response with one scroll closed / one scroll open
  - Good high speed power with both scrolls open
  - Conventional design features (wastegate-type binary scroll valve)
  - Package friendly
- Challenges
  - Mechanical robustness of binary scroll valve
  - Additional control requirement for valve



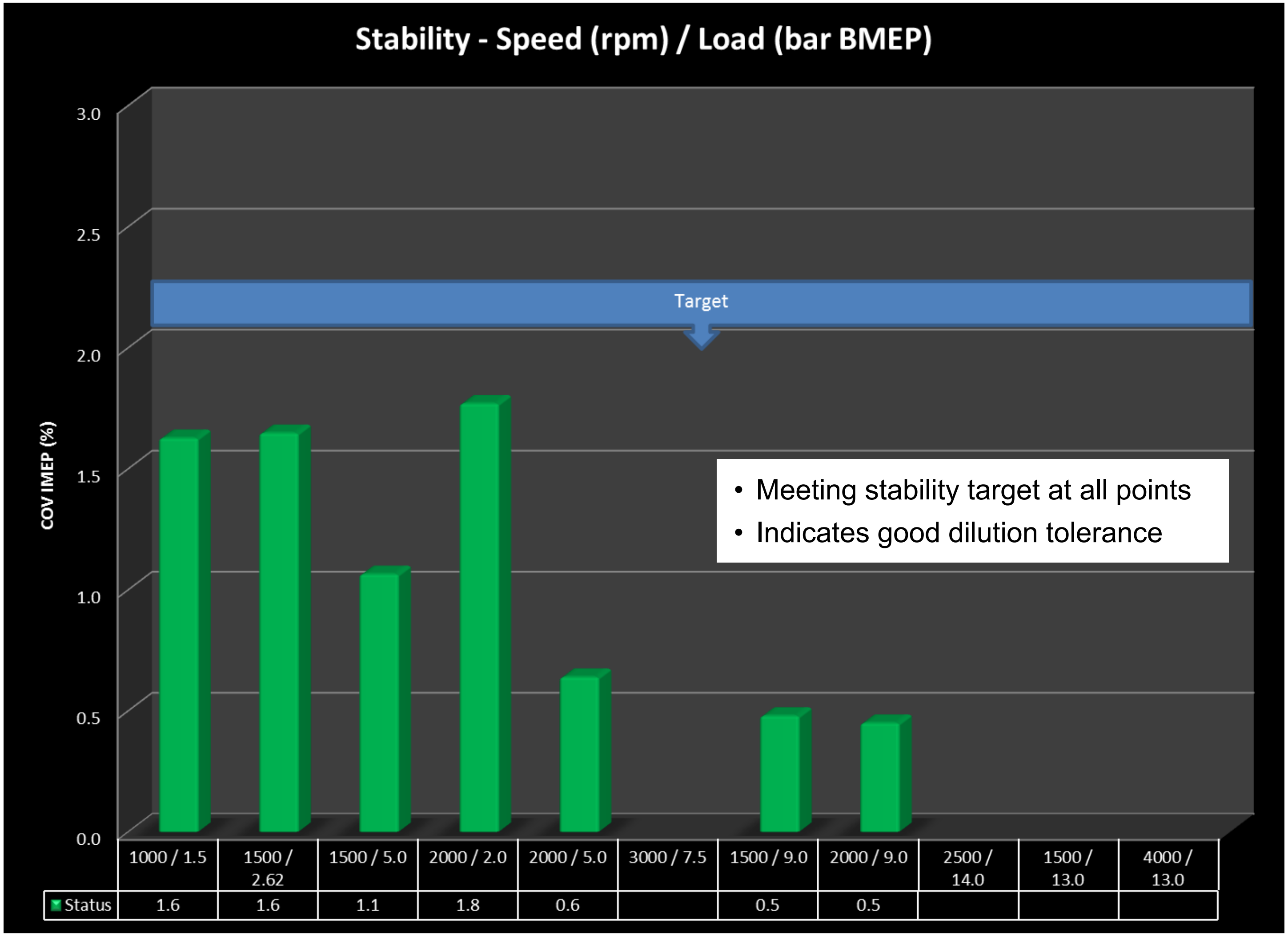


- MCE Evaluation on Dynamometer – Part Load Fuel Consumption

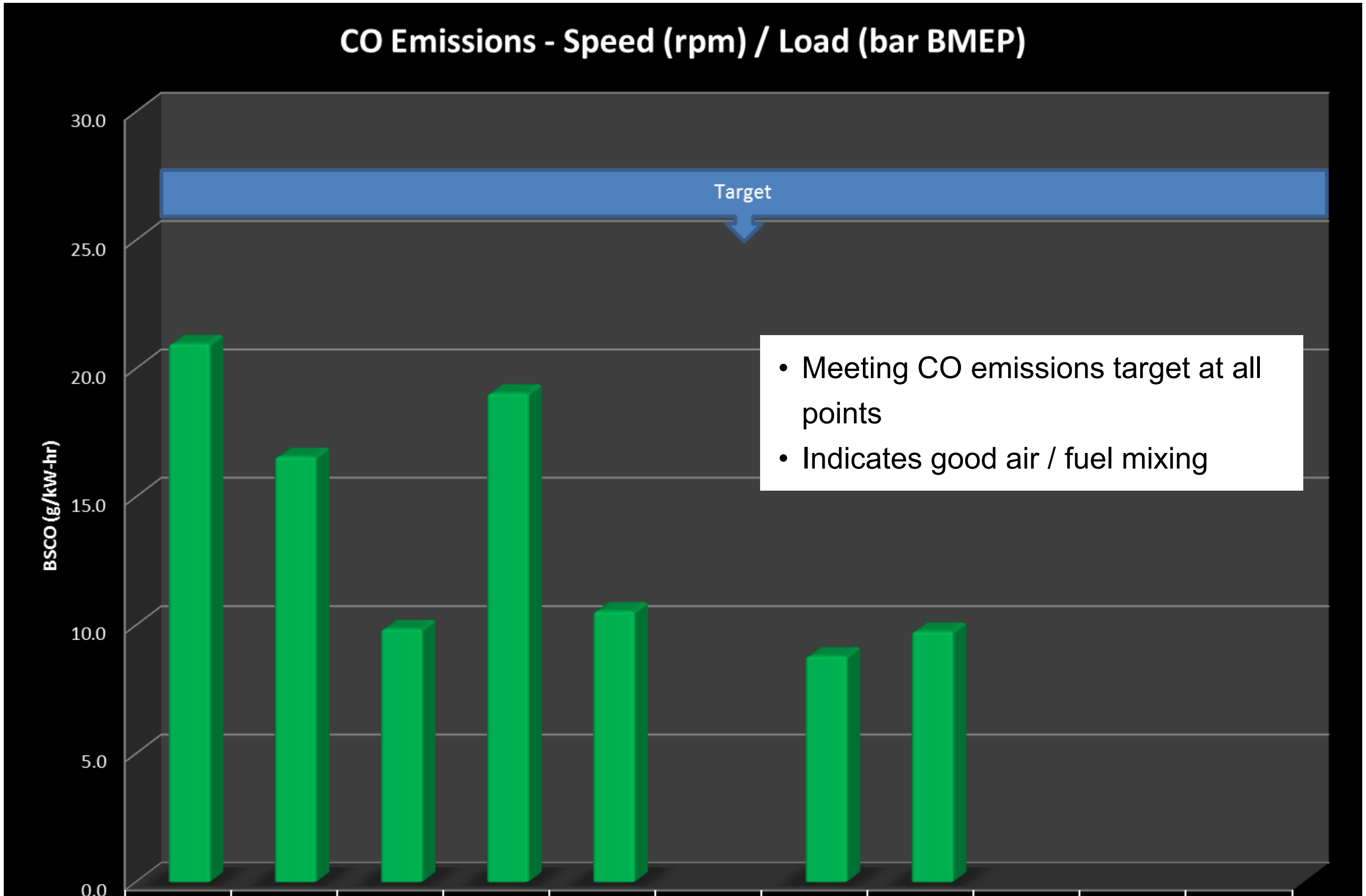


	1000 / 1.5	1500 / 2.62	1500 / 5.0	2000 / 2.0	2000 / 5.0	3000 / 7.5	1500 / 9.0	2000 / 9.0	2500 / 14.0	1500 / 13.0	4000 / 13.0
Target	392	303	250	349	252	231	224	223	218	242	224
Status	400	296	246	346	252		224	223			

- MCE Evaluation on Dynamometer – Part Load Stability



- MCE Evaluation on Dynamometer – Part Load CO Emissions



	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	1500 / 13.0	4000 / 13.0
Status	21.0	16.6	9.9	19.0	10.6		8.8	9.8			

Accomplishments

Research and Advanced Engineering

- Vehicle Build and Development

  ✓ Initiated CAD design and required CAE analyses of new advanced integrated powertrain systems.

    - Torque converter pendulum damper
    - Active powertrain mounts

    Improved fuel economy via preservation of V6 idle & lugging limits; mitigation of I4 firing frequency & 2nd order unbalance

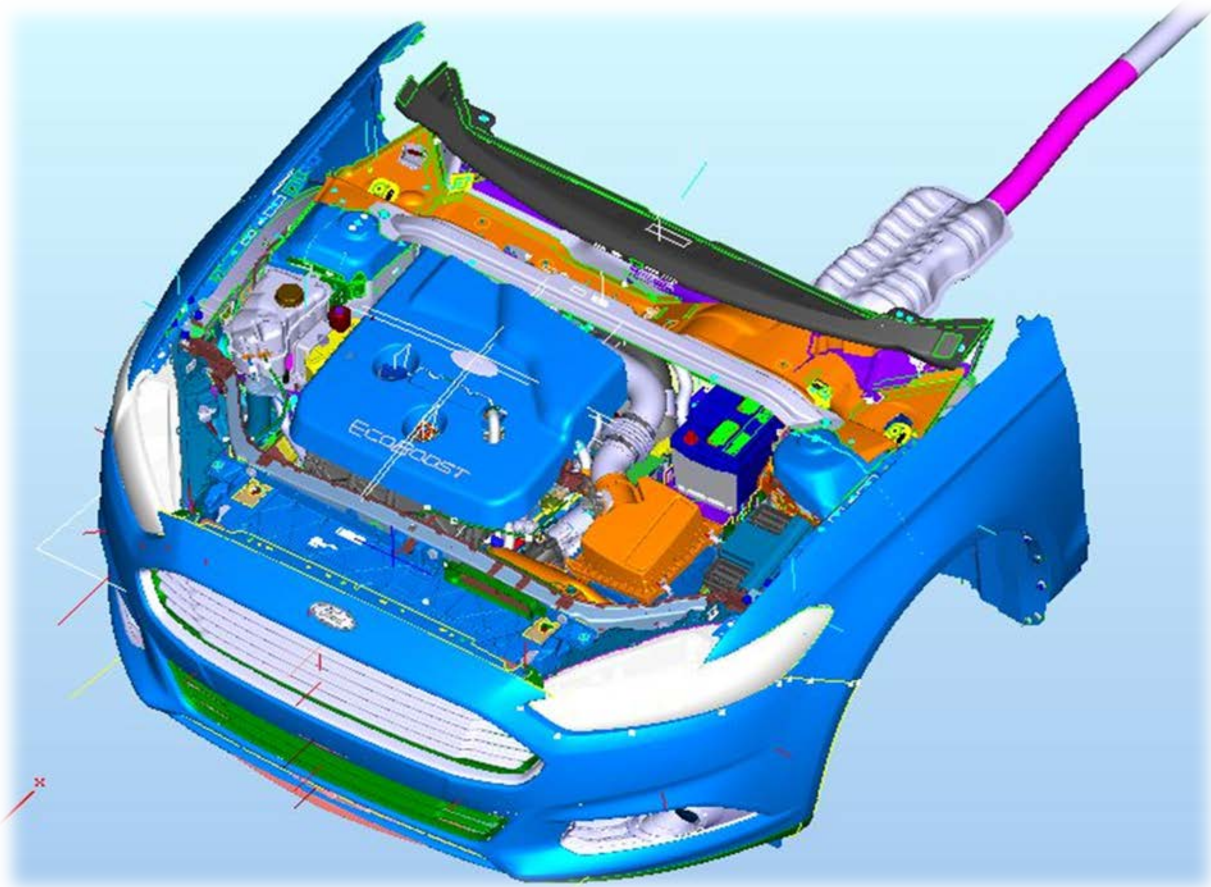
  ✓ Completed CAD design and required CAE analyses of cooling and aftertreatment systems; initiated procurement of cooling and aftertreatment system components.

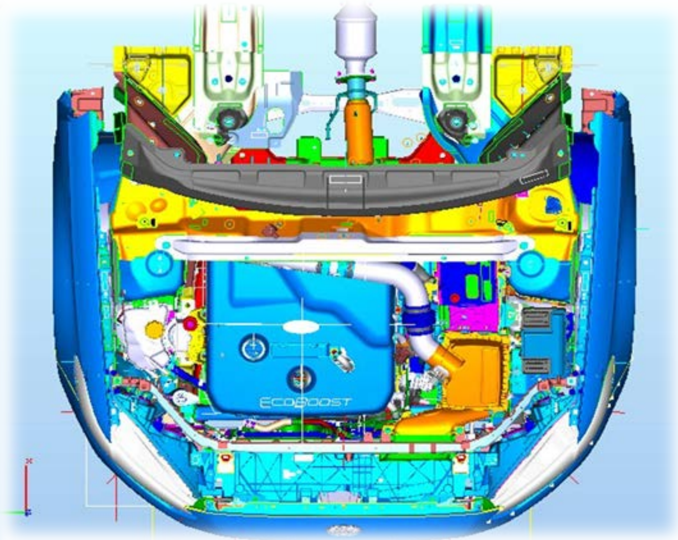
  ✓ Milestone "Demonstration vehicle and components available to start build and instrument" deferred from 12/31/2012 to 08/01/2013.

  ✓ Acquired surrogate vehicle with surrogate GTDI engine; initiated early controls and calibration development tasks to accelerate target vehicle tasks.

Accomplishments

- Vehicle Build and Development – Engine As Installed In 2013 CD391 Fusion





Accomplishments

Research and Advanced Engineering

- Aftertreatment Development
  - Investigated the potential of a TWC + LNT / SCR system to satisfy the HC and NOx slip targets.
    - Assessed catalyst volumes, operating temperatures, lean/rich durations, and lean NOx concentrations; estimated system costs and fuel economy benefits.
  - Investigated the DeSOx capability of an underbody LNT; estimated associated aging impact and tailpipe emission penalties.
    - Determined that reducing TWC OSC levels and employing a lean/rich wobble DeSOx strategy was insufficient to achieve the 700 deg C target DeSOx temperature.
  - Investigated the potential of a TWC + passive SCR system to satisfy the HC and NOx slip targets while improving the DeSOx capability (vs. the TWC + LNT / SCR system).
  - 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.

Collaboration

Research and Advanced Engineering

- Combustion Research (MTU)
  - Progressed all research tasks focused on expansion of dilute engine operating limits

    1) Advanced Ignition & Flame Kernel Development
    2) Advanced Ignition – Impact on Dilute Combustion
    3) Air / Fuel Mixing via PLIF for GDI
    4) Combustion Sensing & Control
    5) Advanced Knock Detection & Control
    6) In-Cylinder Temps & Heat Flux

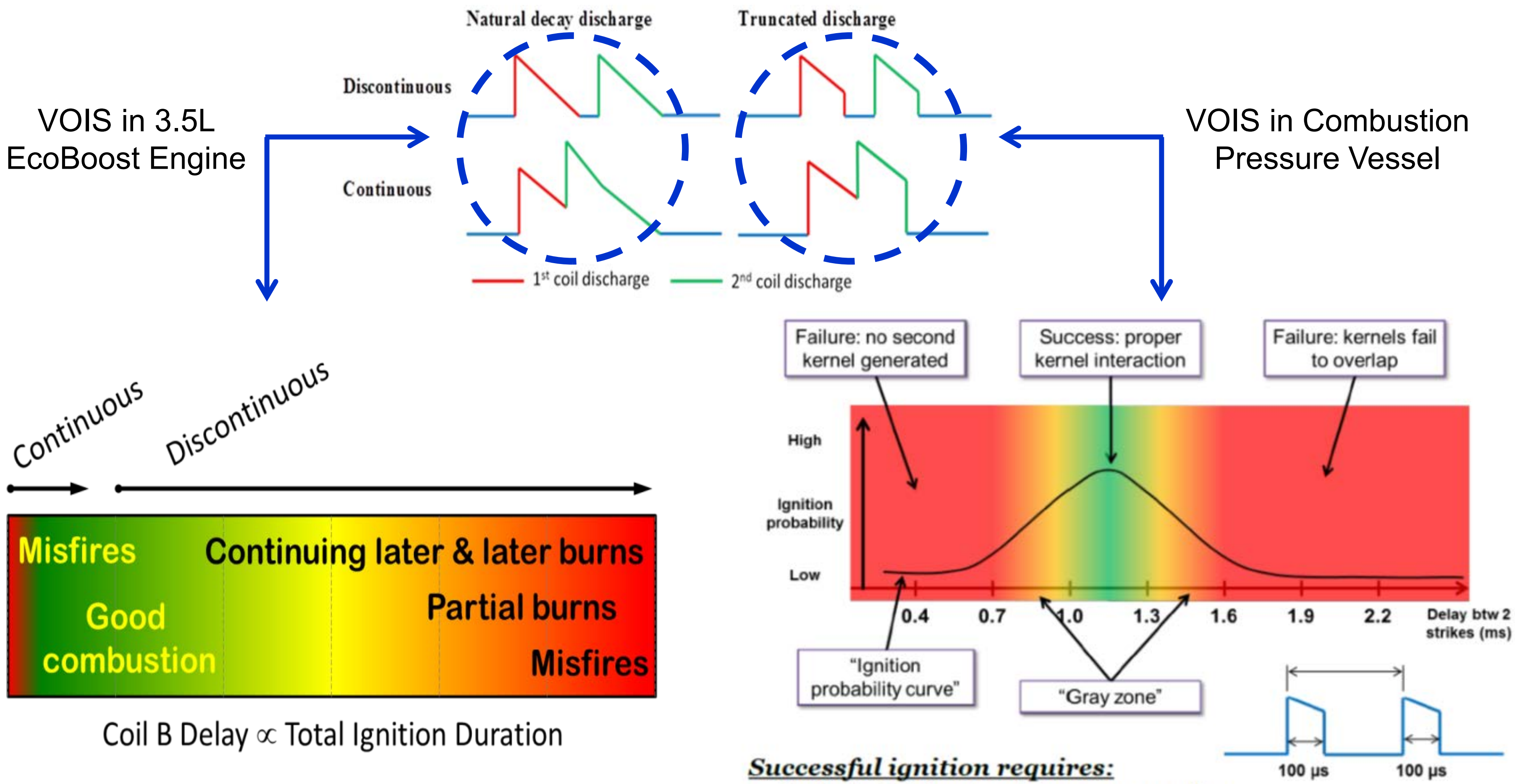
  - Continued development of the high feature combustion pressure vessel:
    - Optimization of the dual fans / shrouds for wide range charge motion representing engine-like mean flow and turbulence intensity conditions
    - Optimization of the variable output ignition system (VOIS) discharge pattern for successful flame initiation and propagation

Collaboration

- Combustion Research (MTU)
  - Continued advanced ignition hardware investigations in the 1st 3.5L EcoBoost engine, including assessment of the dilute engine operating limits (i.e. cooled EGR) as a function of VOIS parameters, spark plug electrode gap, and tumble ratio.

- Continued preparation of the 2nd 3.5L EcoBoost engine for combustion surface temperature measurements, including installation of a wireless telemetry system for piston temperature and heat flux measurements.

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

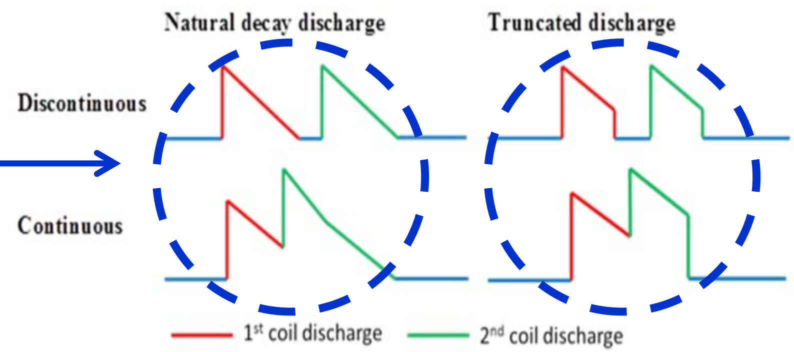


Successful ignition requires:

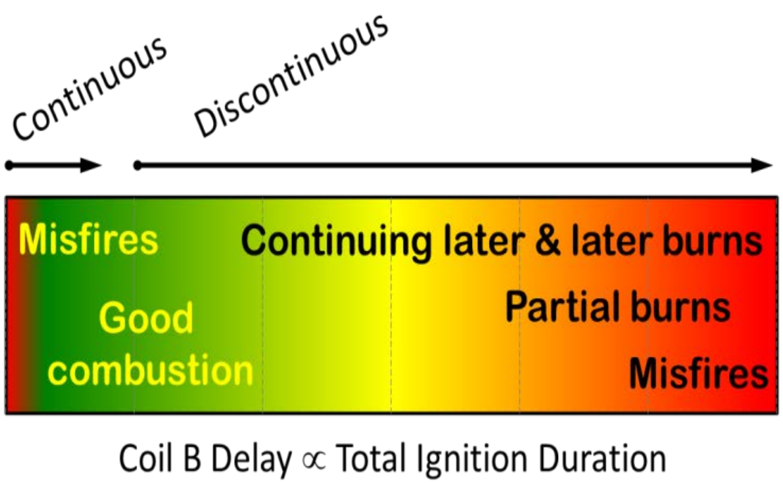
- Optimized delay time between two strikes
- Delay time determined based on turbulence level

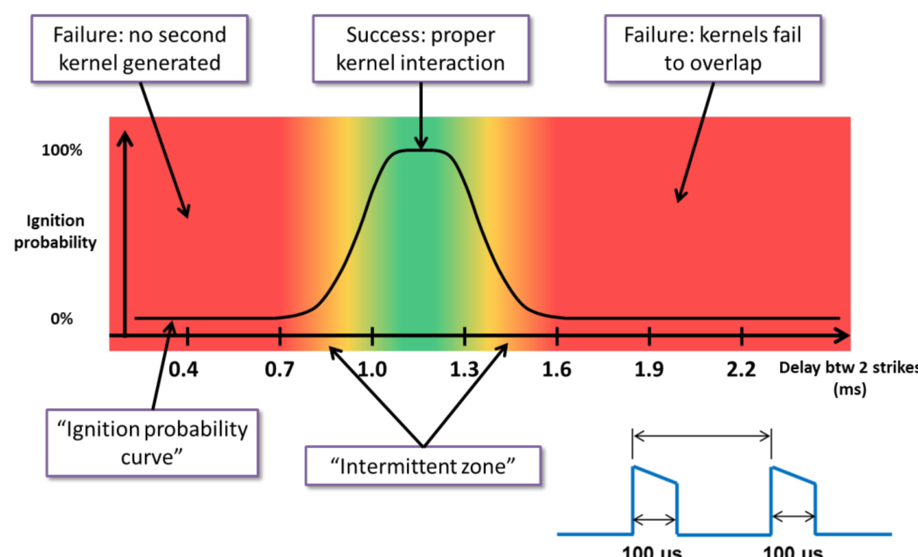
- Optimization of VOIS discharge pattern for successful flame initiation and propagation yields similar results in engine and pressure vessel

VOIS in 3.5L EcoBoost Engine



VOIS in Combustion Pressure Vessel



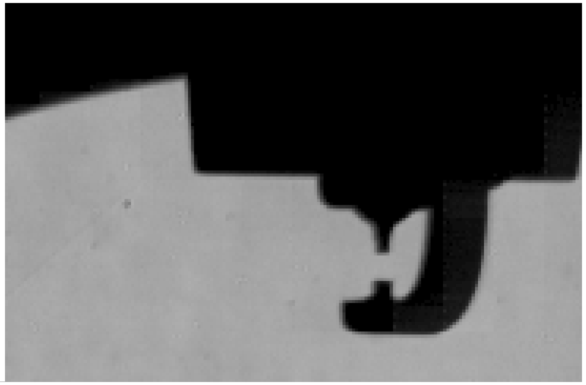


Collaboration

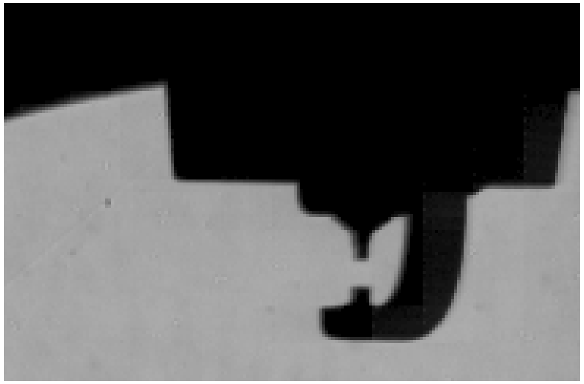
Research and Advanced Engineering

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

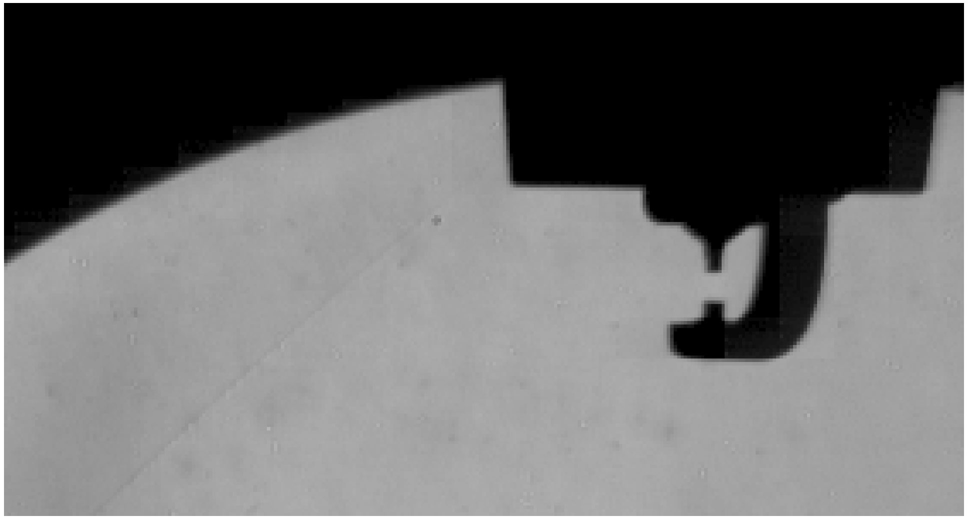
2 Strikes @ 0.7 ms Delay = Failed Ignition



2 Strikes @ 1.6 ms Delay = Failed Ignition



2 Strikes @ 1.0 ms Delay = Successful Ignition!



Future Work

Research and Advanced Engineering

- Budget Period 3 – Engine & Vehicle Development 01/01/2013 – 12/31/2013
  - Dynamometer engine development indicates capability to meet intermediate metrics supporting vehicle fuel economy and emissions objectives
  - Demonstration vehicle and components available to start build and instrument (deferred from 12/31/2012 to 08/01/2013)
  - Vehicle build, instrumented, and development work started
  - Aftertreatment system development indicates capability to meet intermediate metrics supporting emissions objectives
  - Project management plan updated
- Budget Period 4 – Vehicle Development 01/01/2014 – 12/31/2014
  - Vehicle demonstrates greater than 25% weighted city / highway fuel economy improvement and Tier 2 Bin 2 emissions on FTP-75 test cycle

Summary

- 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 2 Bin 2 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, and development tasks with material accomplishments to date.

- The outlook for 2013 is stable, with accomplishments anticipated to track the original scope of work and planned tasks, with the exception of milestone "Demonstration vehicle and components available to start build and instrument" deferred from 12/31/2012 to 08/01/2013.

Technical Back-Up

Research and Advanced Engineering

Concept Evaluation

Research and Advanced Engineering

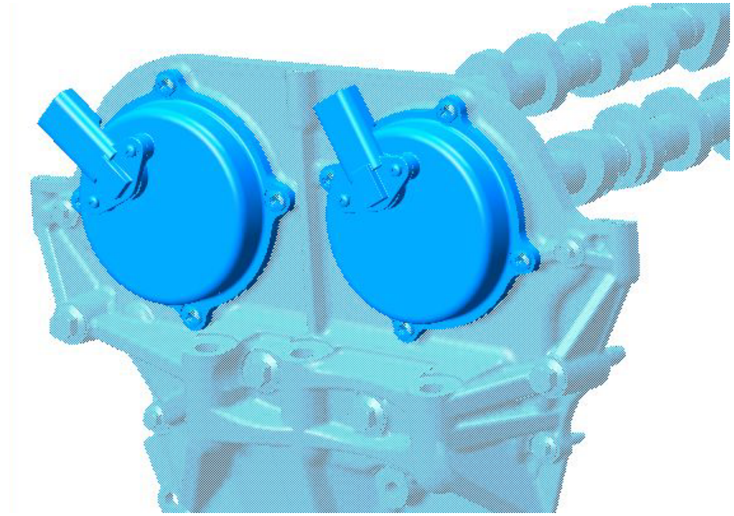
- Detailed, cycle-based CAE analysis of fuel economy contribution of critical technologies

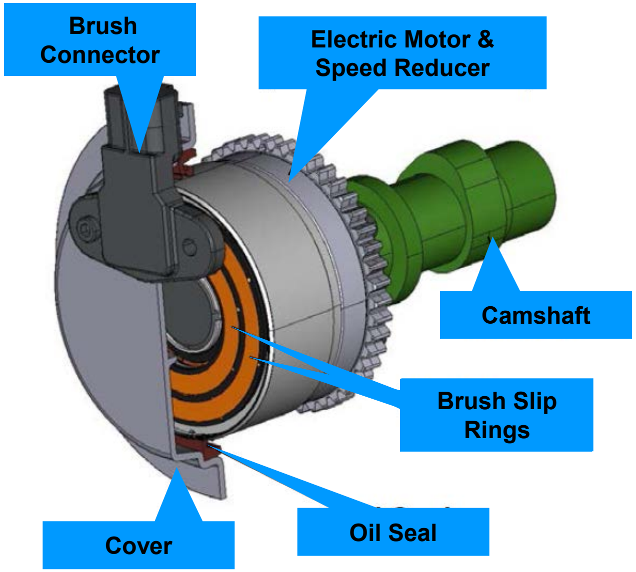
Architecture / System Assumption	% Fuel Economy	
3.5L V6 ⇨ 2.3L I4 High Expansion Ratio Architecture	+	15.6% - Engine Architecture / Downsizing
583 ⇨ 565 cm^3 Displacement / Cylinder	~	
1.07 ⇨ 0.93 Bore / Stroke	~	
10.3:1 ⇨ 11.5:1 Compression Ratio	+	
PFI ⇨ Transverse Central DI	-	
iVCT ⇨ Electric tiVCT	+	
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

Electric tiVCT

- Advantages
  - Cam position control independent of engine speed, oil pressure, & oil temperature
  - Good shifting velocity ~ 300 /sec
  - Good shifting range ~ 80
- Challenges
  - Mechanical robustness of brushes, electric motor, and speed reducer
  - Additional control requirement for electric motor
  - Package diameter & length

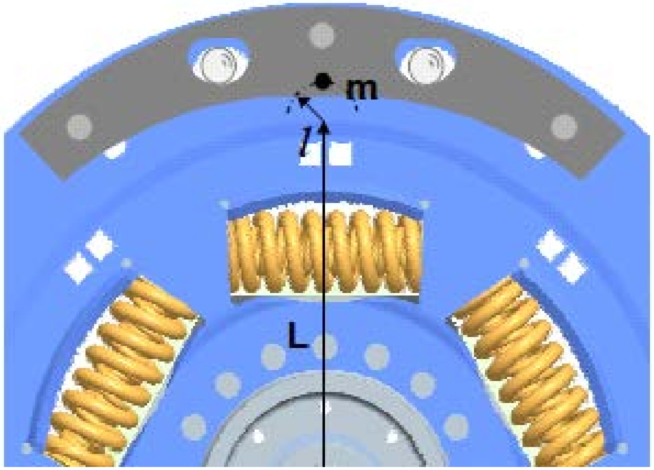


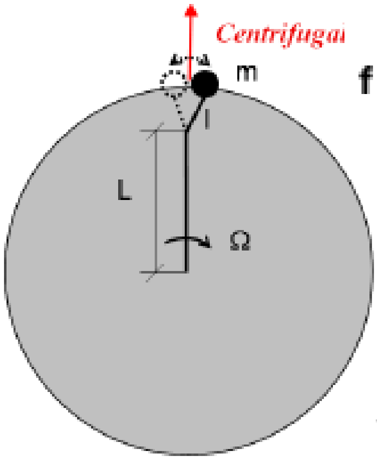


Torque converter pendulum damper

- Advantages
  - Improved fuel economy via preservation of V6 idle & lugging limits; mitigation of I4 firing frequency & 2nd order unbalance
  - Good overall NVH
  - No additional control requirement

- Challenges
  - Additional mass & inertia
  - Mechanical robustness of pendulum components
  - Package diameter & length





$$f = \sqrt{\frac{\Omega^2 L}{l}} \cdot \frac{1}{2\pi}$$

Tuning Frequency

$$f_T = q \cdot \Omega \cdot \frac{1}{2\pi}$$

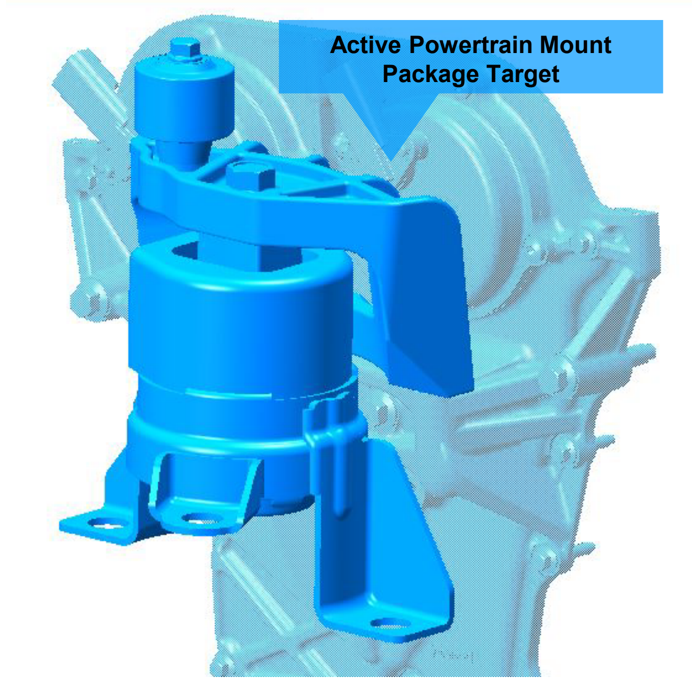
Tuning Order

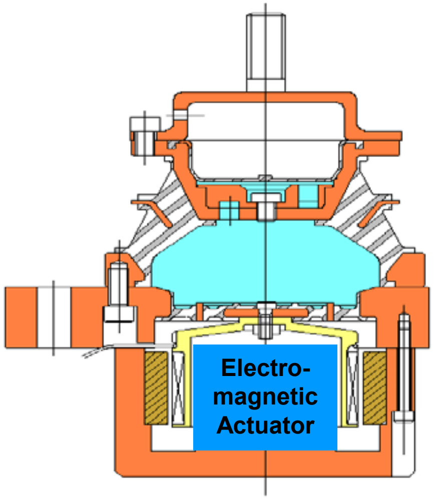
$$q = \sqrt{\frac{L}{l}}$$

✓ Tuned to reject I4 2nd order unbalance

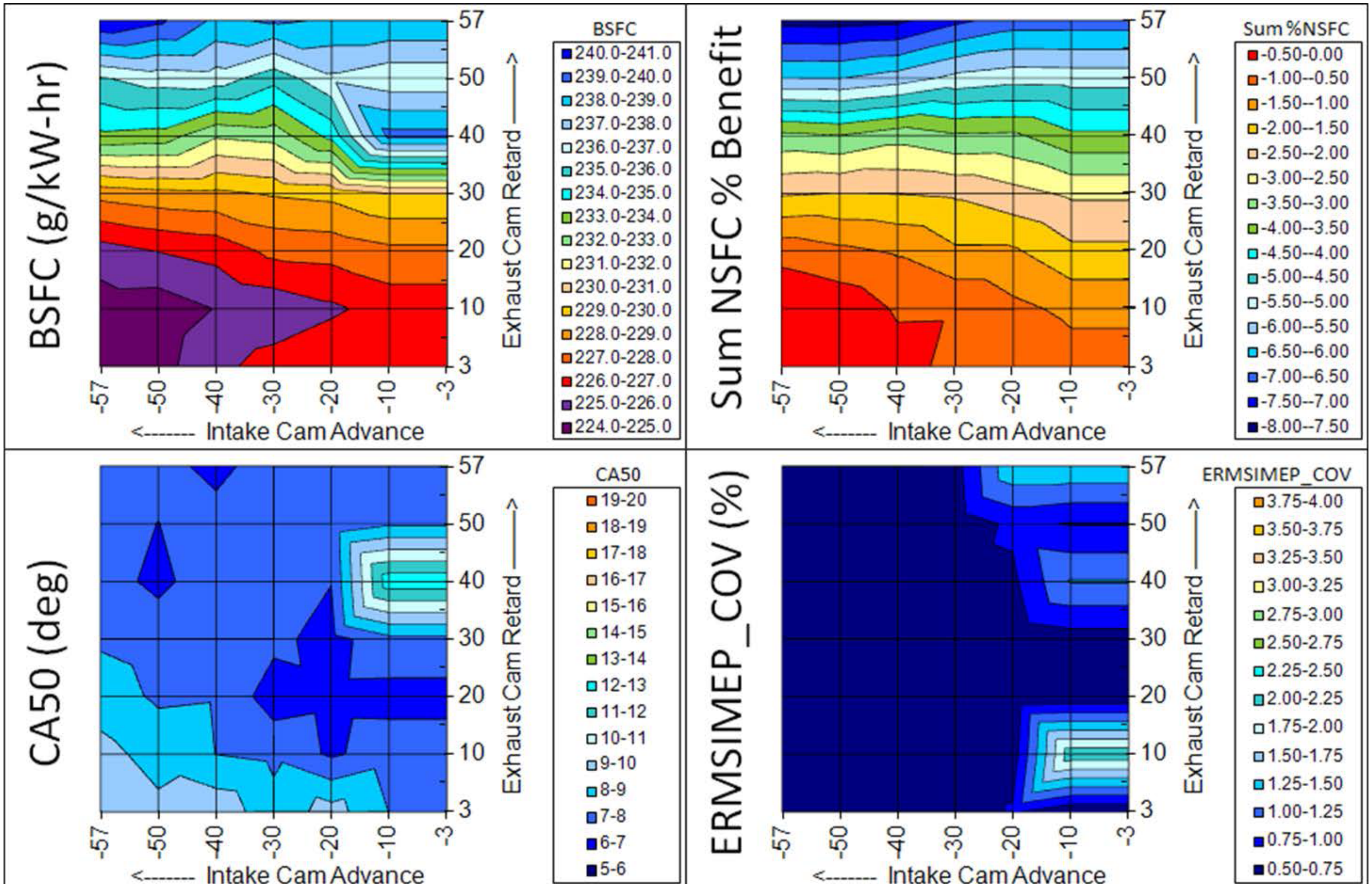
Active powertrain mounts

- Advantages
  - Improved fuel economy via preservation of V6 idle & lugging limits; mitigation of I4 firing frequency & 2nd order unbalance
  - Improved fuel economy, reduced mass & inertia via deletion of balance shaft module
  - Good overall NVH
- Challenges
  - Dynamic range and unbalance force of authority
  - Mechanical robustness of electromagnetic actuator
  - Additional control requirement for actuator
  - Package diameter & height





- MCE Evaluation on Dynamometer – Cam Timing Optimization 2000 rpm / 9.0 bar BMEP



Collaboration - MTU

Research and Advanced Engineering

	Research Area	Deliverables	Pressure Vessel	Engine Dyno
1	Advanced Ignition – Ignition and Flame Kernel Development	Gain insight to the fundamental physics of the interaction of combustion system attributes & ignition system design variables relative to both design factors & noise factors; use results to develop an analytical spark discharge model.	✓	
2	Advanced Ignition – Impact on Lean and Dilute	Validate the findings from the pressure vessel & predictions of the resultant model on a mature combustion system, focusing on dilute & lean operating conditions.		✓
3	Planer Laser Induced Fluorescence	Apply laser-based diagnostics to characterize multi-phase fuel / air mixing under controlled high pressure & temperature conditions; use data for CFD spray model development & spray pattern optimization.	✓	
4	Combustion Sensing and Control	Assess production viable combustion sensing techniques; detect location of 50% mass fraction burned & combustion stability for closed loop combustion control.		✓
5	Advanced Knock Detection with Coordinated Engine Control	Compare stochastic knock control to various conventional control techniques.		✓
6	Combustion Surface Temperature	Measure instantaneous temperatures of combustion chamber components under lean, dilute, & boosted operation to improve numerical models and reduce knock tendency.		✓