Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development

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Ford Research and Advanced Engineering

05/18/2012

Project ID: ACE065

Overview

- Timeline
  - Project Start 10/01/2010
  - Project End 12/31/2014
  - Completed 30%
- Total Project Funding
  - DOE Share $15,000,000.
  - Ford Share $15,000,000.
  - Funding in FY2011 $10,365,344.
  - Funding in FY2012 $ 9,702,590.
- 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

Research and Advanced Engineering

- 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.

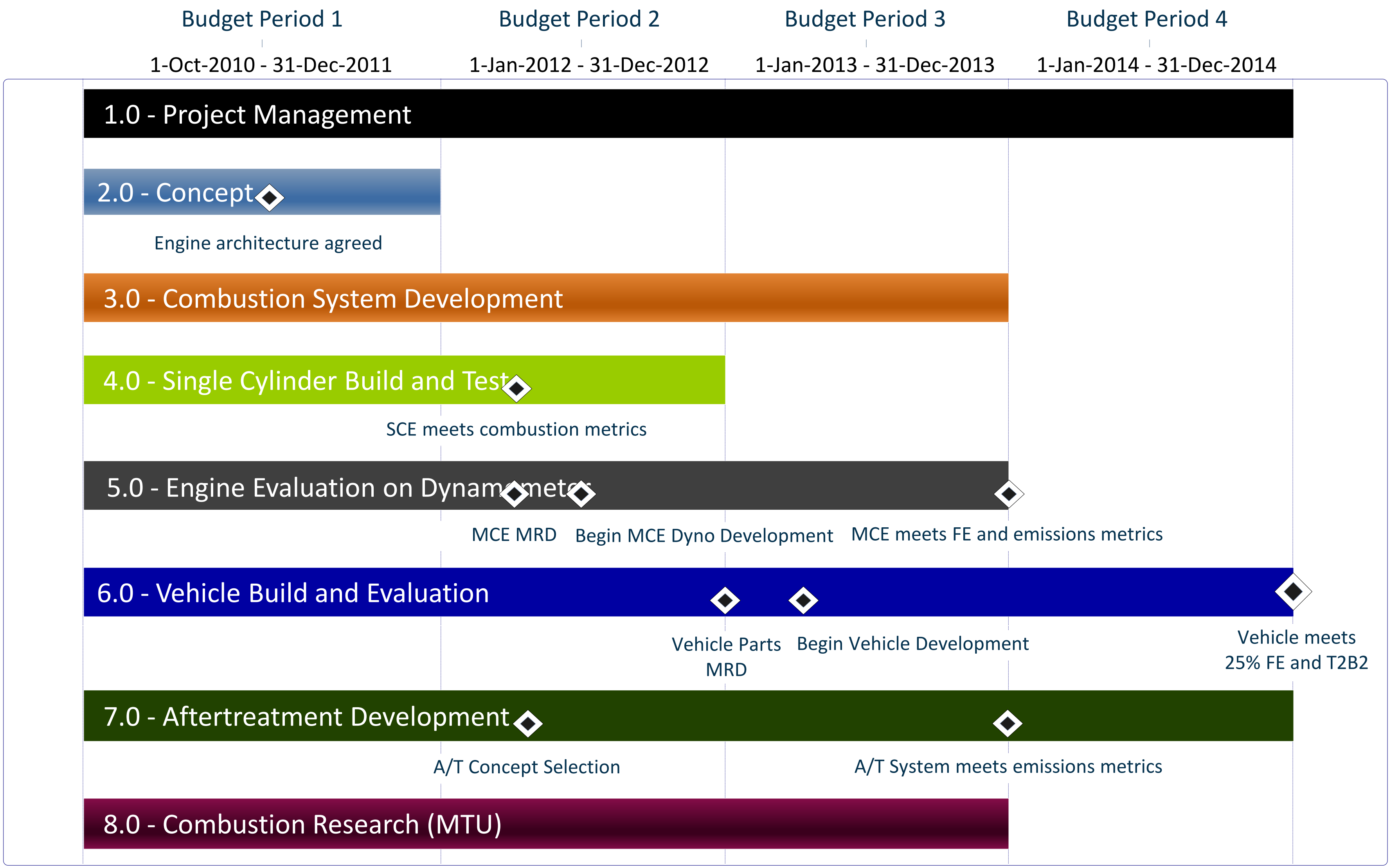
- MTU Objectives:
  - Support Ford Motor Company in the research and development of advanced ignition concepts and systems to expand the dilute / lean engine operating limits.

Approach

- 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

Research and Advanced Engineering



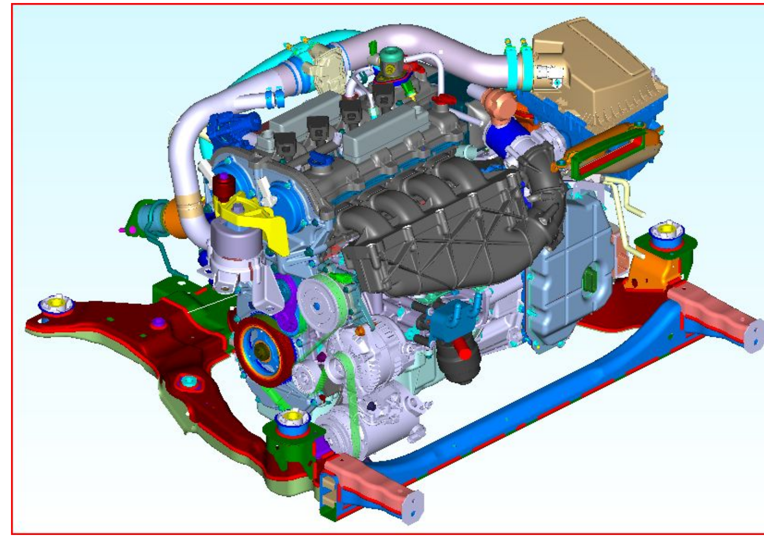
Accomplishments

- Concept Evaluation
  - ✓ Selected a 2.3L I4 high expansion ratio engine architecture to “right-size” the engine with future North American, high volume, CD-size (i.e. mid-size) vehicle applications.
    - ✓ Developed top level engine attribute assumptions, architecture assumptions, and systems assumptions to support program targets.
    - ✓ Developed detailed fuel economy, emissions, performance, and NVH targets to support top-level assumptions.
    - ✓ Developed individual component assumptions to support detailed targets, as well as to guide combustion system, single-cylinder engine, and multi-cylinder engine design and development.
    - ✓ Completed detailed, cycle-based CAE analysis of fuel economy contribution of critical technologies to ensure vehicle demonstrates 25% weighted city / highway fuel economy improvement

Accomplishments

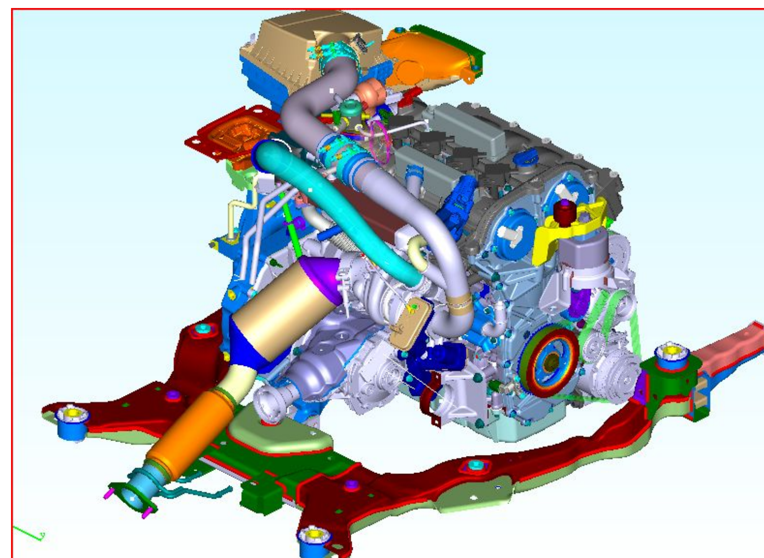
- Attribute Assumptions

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



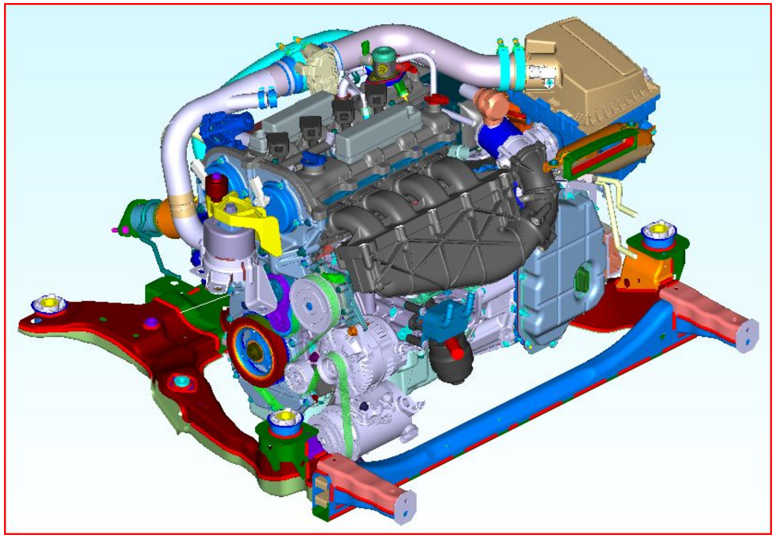
Accomplishments

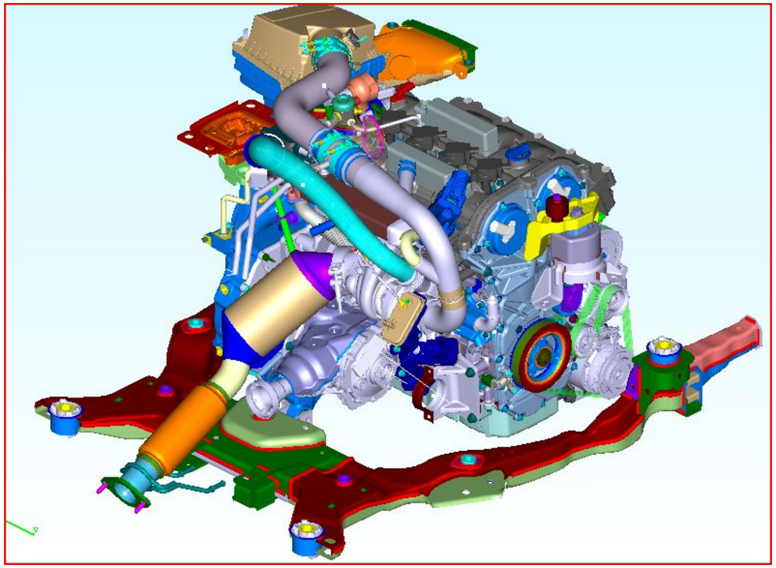
Research and Advanced Engineering

- 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

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

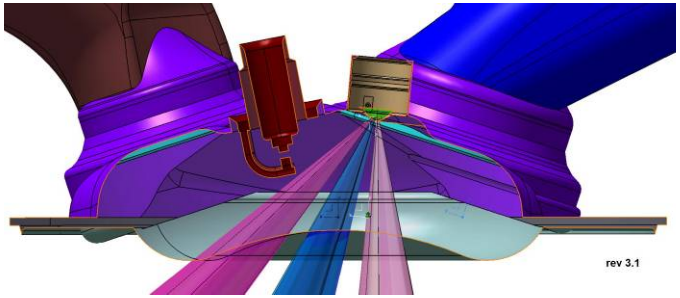
Architecture / System Assumption	% Fuel Economy	
3.5L V6 ⇨ 2.3L I4 High Expansion Ratio Architecture	+	15.6% - Engine Architecture / Downsizing
583 ⇨ 565 cm^3 Displacement / Cylinder	~	
1.07 ⇨ 0.93 Bore / Stroke	~	
10.3:1 ⇨ 11.5:1 Compression Ratio	+	
PFI ⇨ Transverse Central DI	-	
iVCT ⇨ Electric tiVCT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

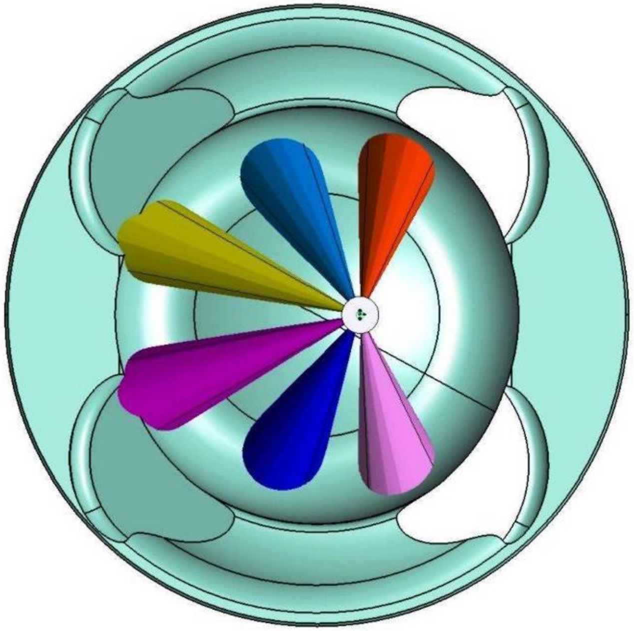
Research and Advanced Engineering

- Combustion System Development
  - ✓ Completed detailed MESIM (Multi-dimensional Engine SIMulation) analyses to design and develop an advanced lean combustion system, inclusive of intake and exhaust ports, combustion chamber, piston top surface, and injector specifications.
  - 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

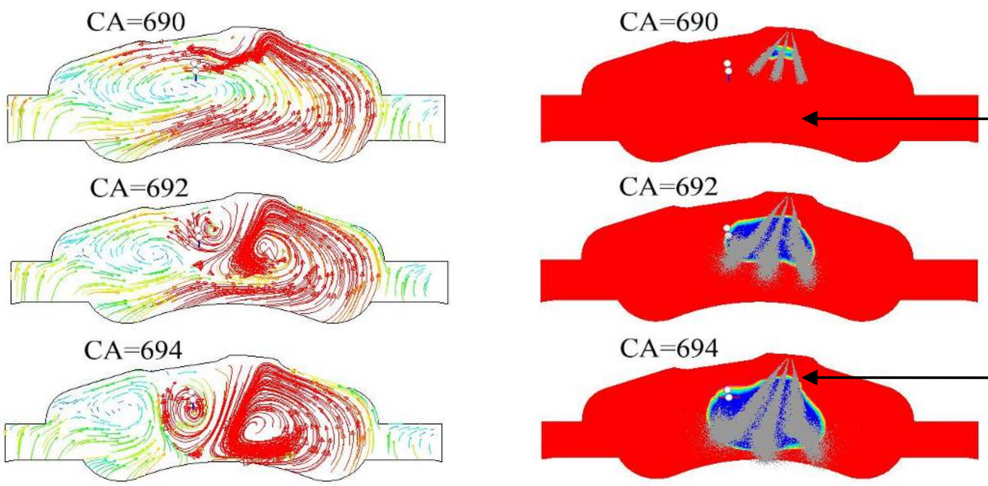


Accomplishments

Research and Advanced Engineering

- Advanced lean combustion system includes “micro” stratified charge capability

Air Flow & Air / Fuel Spatial & Temporal Evolution



“Micro” Stratified Charge

=

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

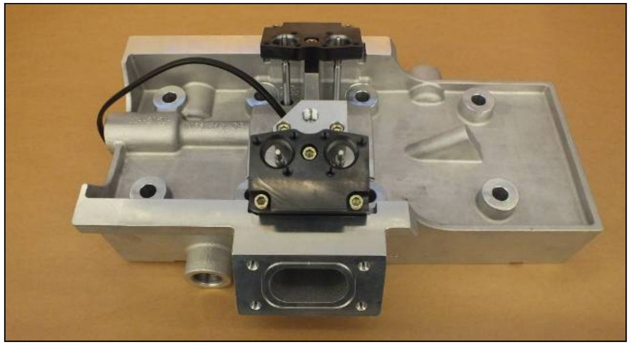
+

- 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, thereby enabling a cost-effective LNT / SCR system

- Single Cylinder Build and Test
  - ✓ Generated surrogate single-cylinder engine data to design and develop the advanced lean combustion capability, with primary emphasis on maximizing fuel economy while minimizing NOx and PM emissions.

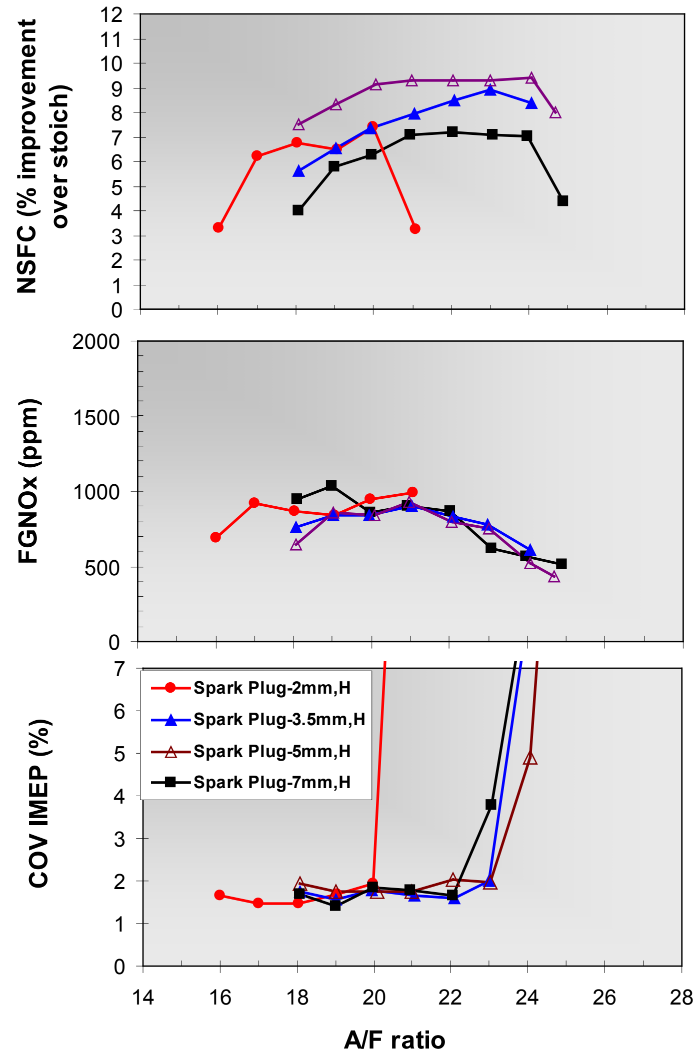
Single-Cylinder Engine Cylinder Head w/ Fully Flexible Valvetrain



Spark Plug Protusion & Shrouding Matrix

Spark Plug #	1	2		3		4	
Protrusion (mm)	2	3.5		5		7	
Shrouding (mm)	0	0	1.5	1.5	3	3	5
							

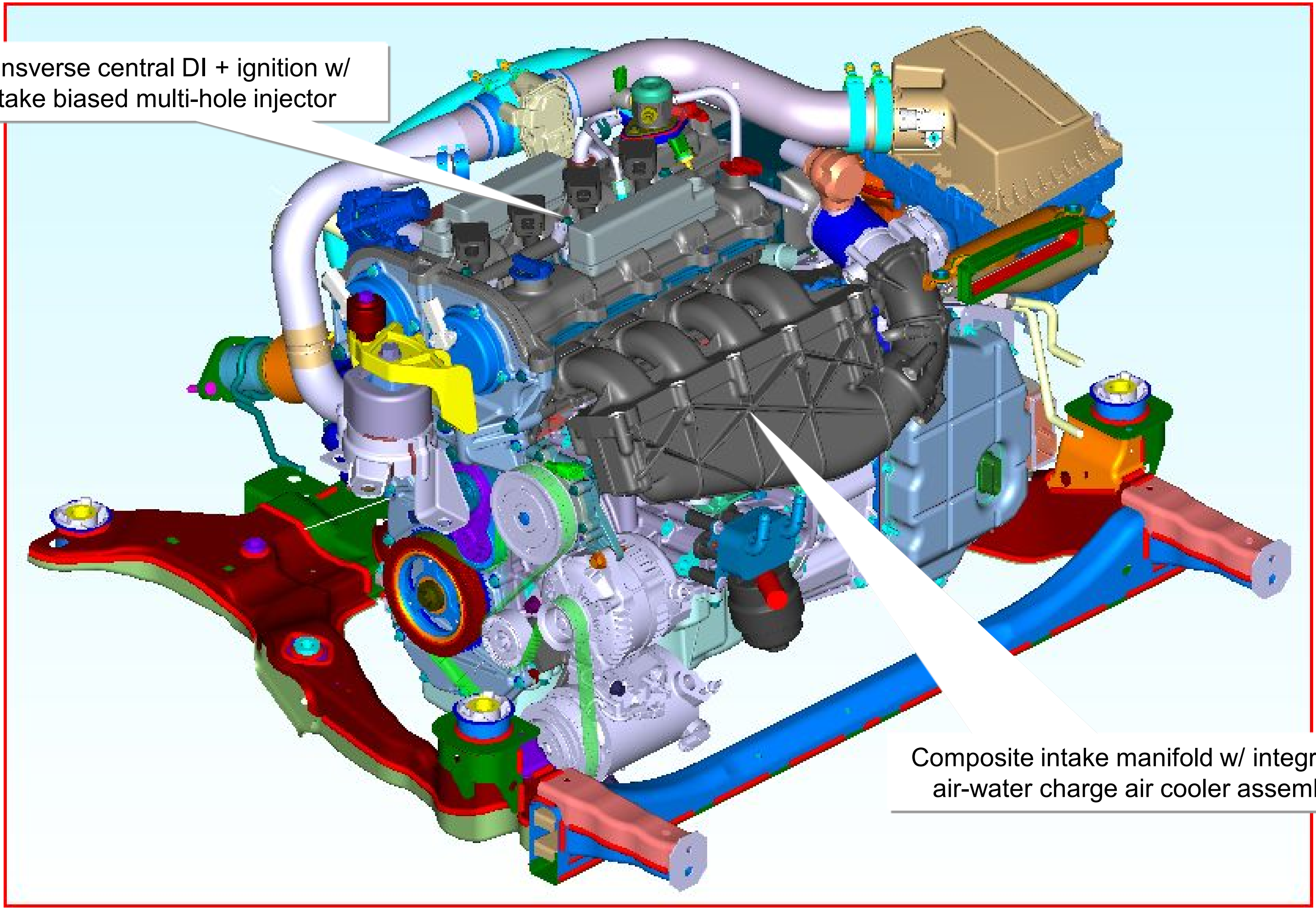
Spark Plug Protrusion & Shrouding Assessment



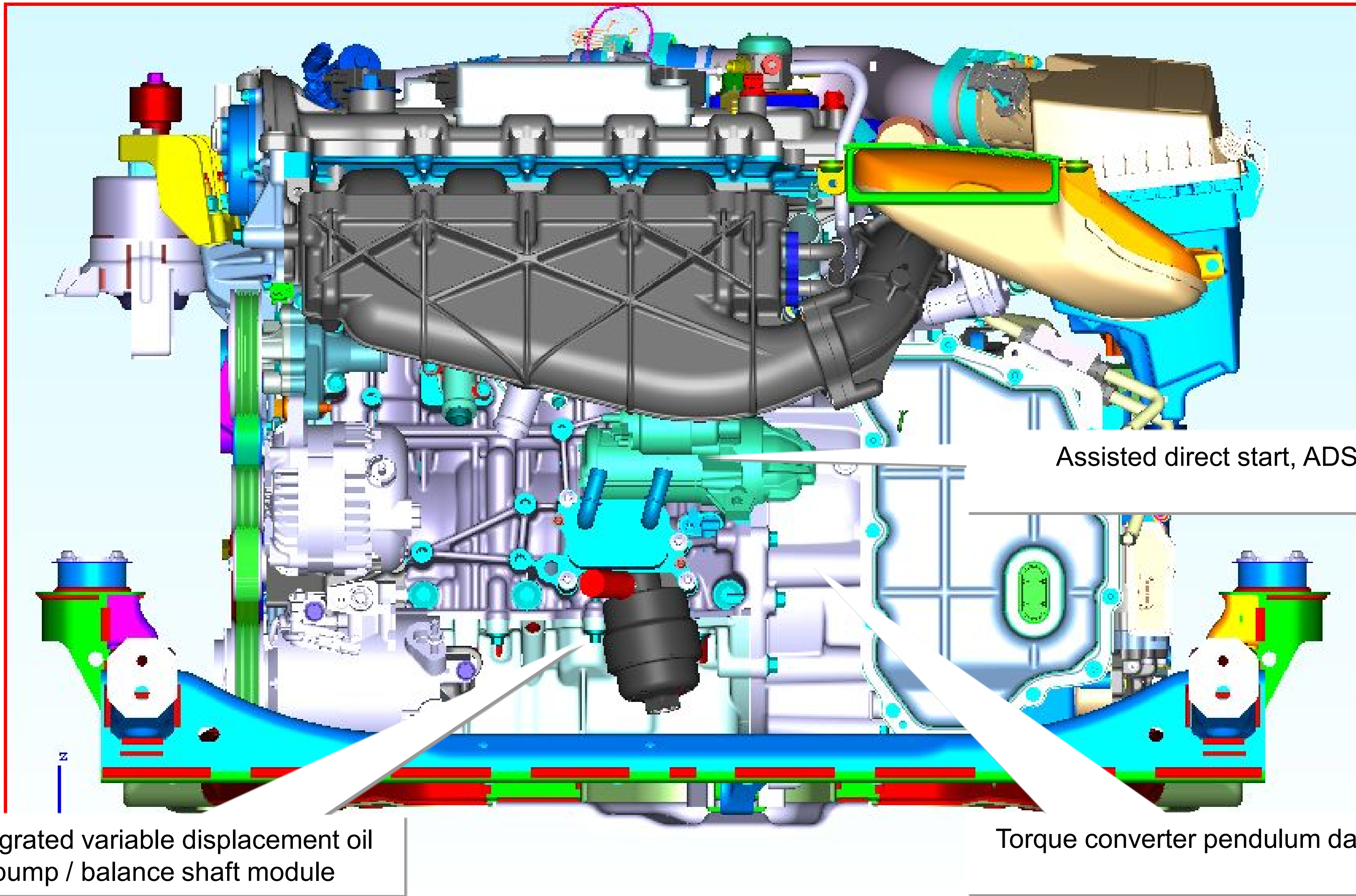
Accomplishments

- Engine Design / Procure / Build
  - ✓ Completed CAD design of new 2.3L multi-cylinder engine, inclusive of all base engine components, advanced engine systems, and advanced integrated powertrain systems
  - ✓ Completed required CAE analyses (acoustic, structural, thermo-mechanical, etc.), in support of CAD design of critical components and systems
  - ✓ Initiated component and systems orders to support multi-cylinder engine builds

Accomplishments



Accomplishments



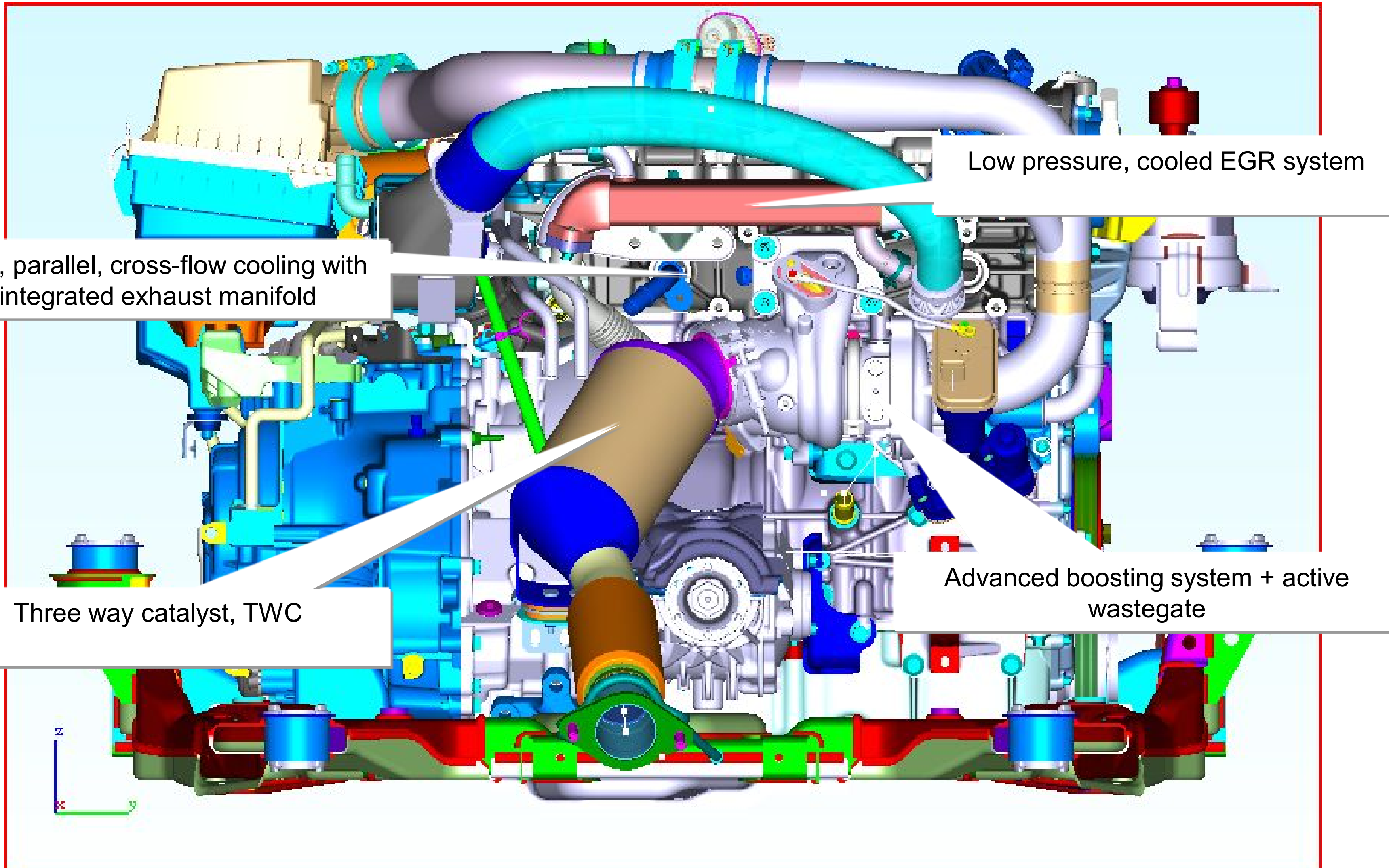
Assisted direct start, ADS

Integrated variable displacement oil pump / balance shaft module

Torque converter pendulum damper

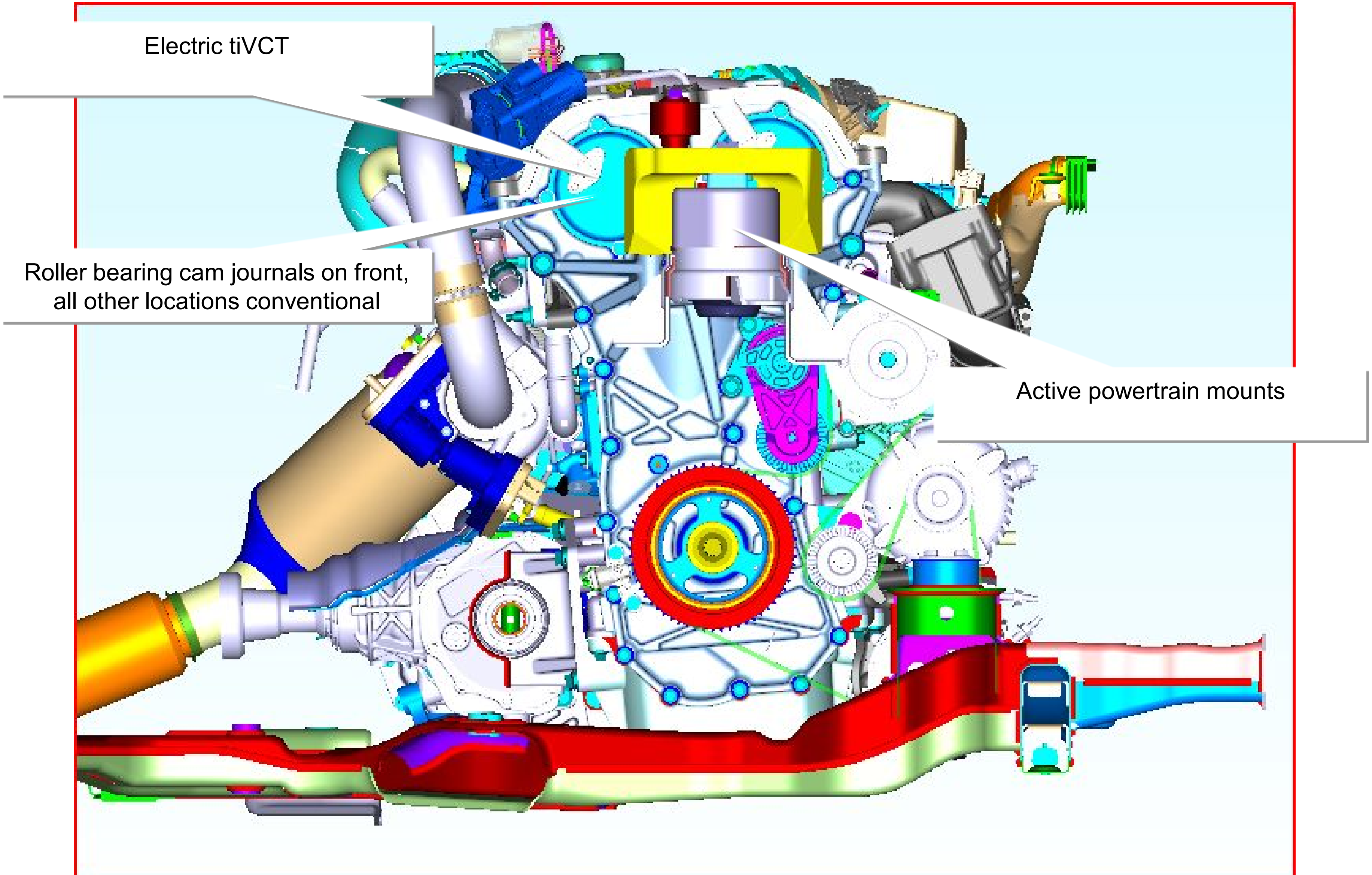
Accomplishments

Research and Advanced Engineering



Accomplishments

Research and Advanced Engineering

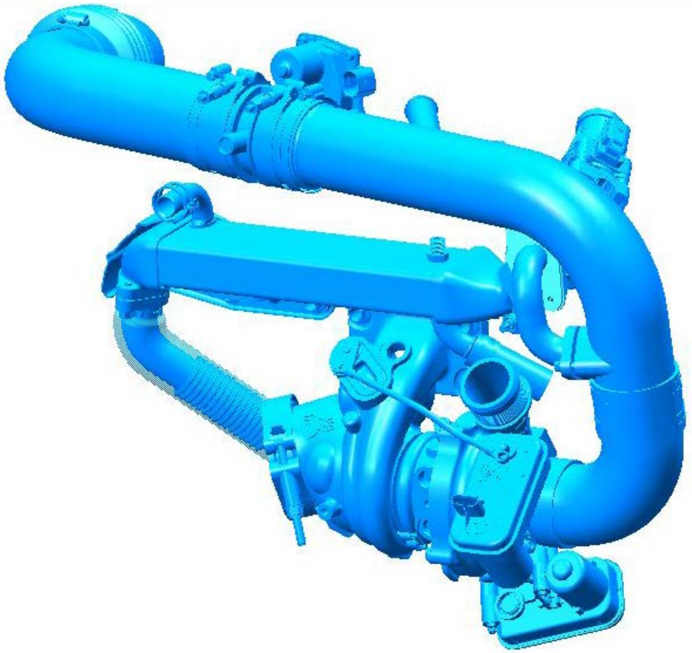


Accomplishments

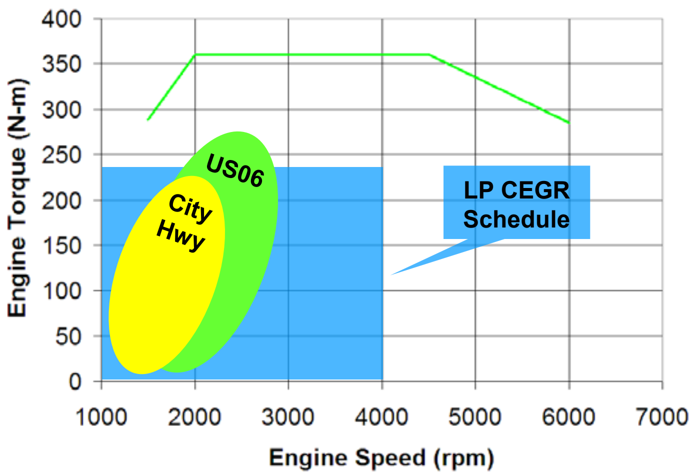
Research and Advanced Engineering

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



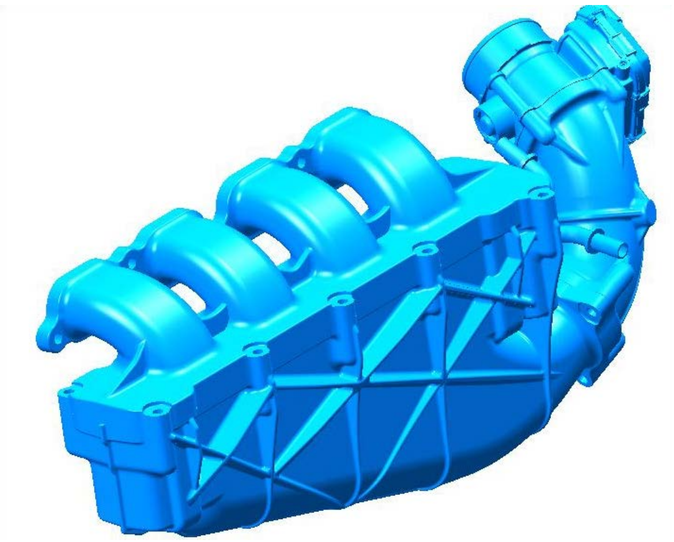
- Challenges
  - Transport delay during speed & load transients
  - Mechanical robustness of charge air cooler and compressor due to EGR exposure
  - Additional controls requirements for EGR valve and throttle

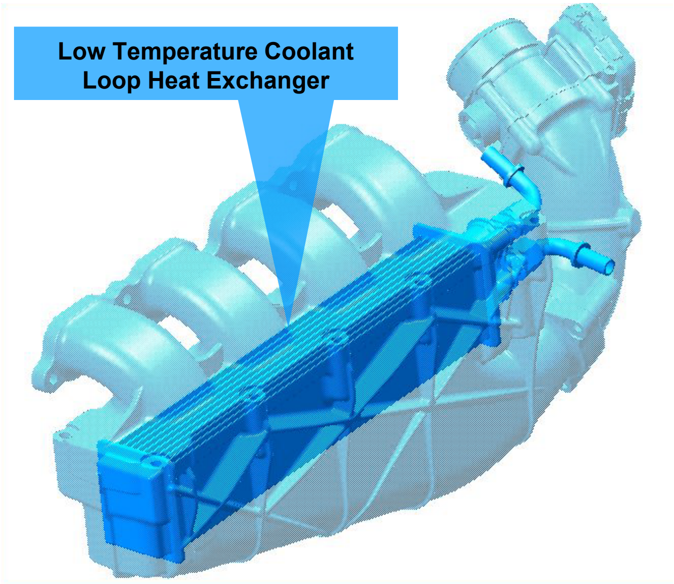


Accomplishments

Composite intake manifold w/ integrated air-water charge air cooler assembly

- Advantages
  - Good low speed transient response via low boosted volume
  - Good high speed power via low pressure drop
  - Synergistic w/ low pressure, cooled EGR via minimum transport delay
  - Package friendly
- Challenges
  - Mechanical robustness of low temperature coolant loop heat exchangers & pump
  - Additional control requirement for pump

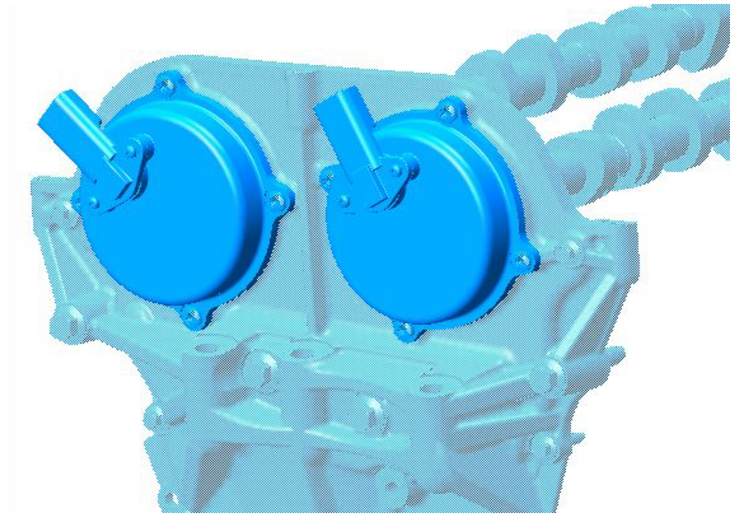


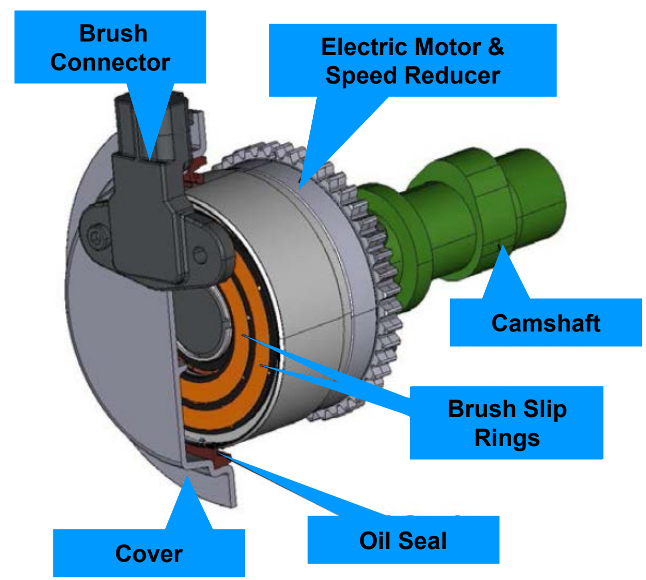


Accomplishments

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



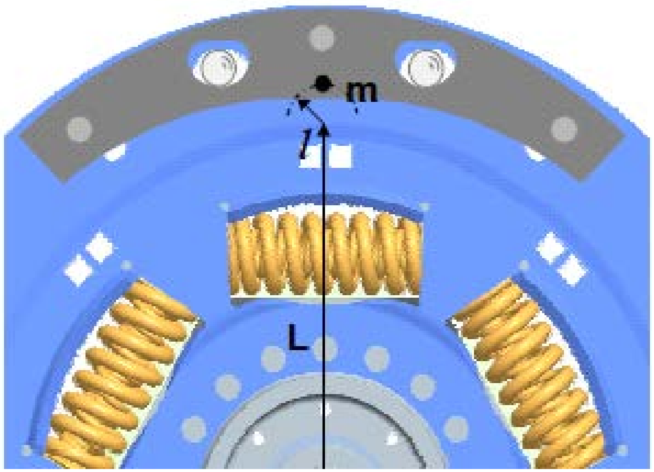


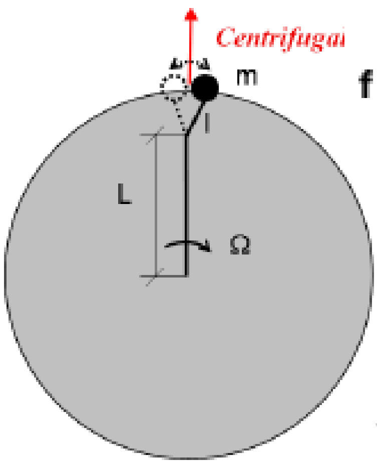
Accomplishments

Research and Advanced Engineering

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

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

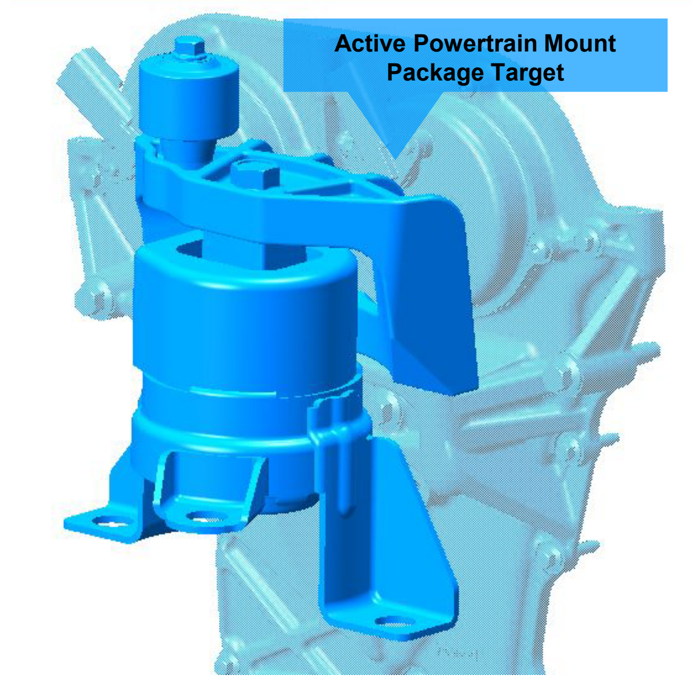
Tuning Order

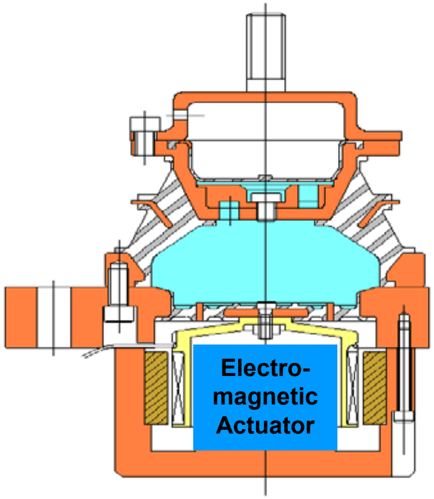
$$q = \sqrt{\frac{L}{l}}$$

✓ 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





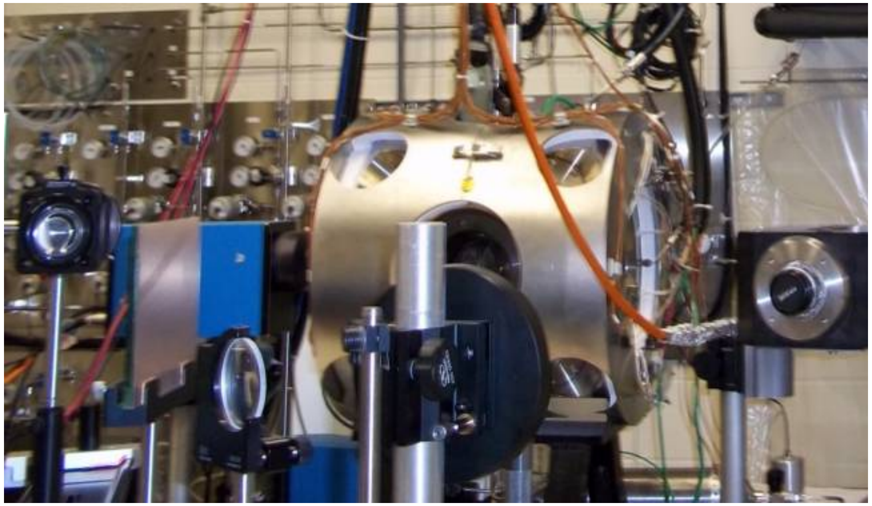
Accomplishments

- Aftertreatment Development: Laboratory Flow Reactor & Analytical Assessment
  - 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; estimating system costs and fuel economy benefits.
    - Assessed TWC + LNT formulations with reduced oxygen storage capacity thus enabling reduced rich purge durations; estimating fuel economy benefits.
  - Investigated the DeSOx capability of an underbody LNT; estimated associated aging impact and tailpipe emission penalties.
  - 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).
    - Assessed catalyst volumes, operating temperatures, lean / rich durations, and lean / rich NOx concentrations; estimating system costs and fuel economy benefits.

Collaboration

Ford Research and Advanced Engineering

- Ford has partnered with Michigan Technological University on expansion of dilute and lean engine operating limits
- Required for effective utilization of cooled EGR and advanced lean combustion technologies
- MTU has demonstrated expertise in these areas
- Combustion research progresses through 2013, utilizing various analytical & experimental tools, with continuous feedback to Ford tasks



High Feature Combustion Pressure Vessel

- ✓ Multiple optical access portals
- ✓ Multiple camera systems
- ✓ Multiple gasesous fuels accurately premixed in large holding tank for homogeneity and repeatability
- ✓ Dual fans for wide range charge motion
- ✓ Adapters for production spark plugs

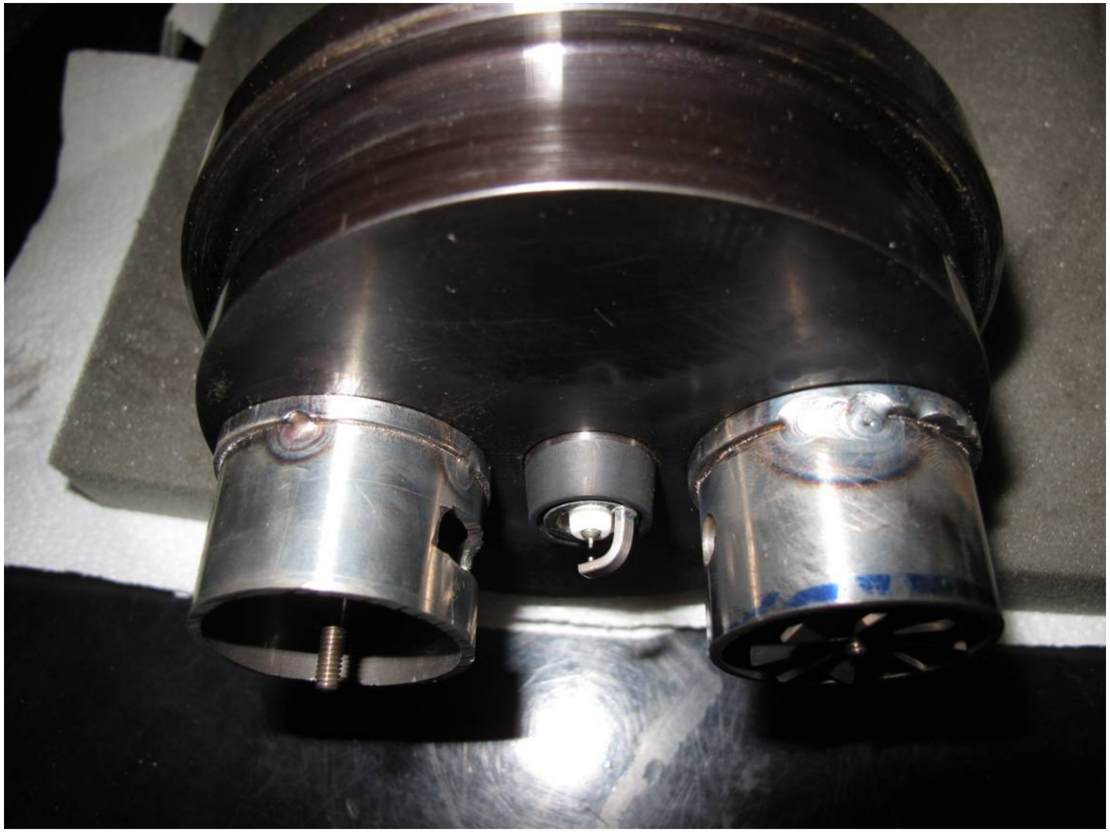
Collaboration

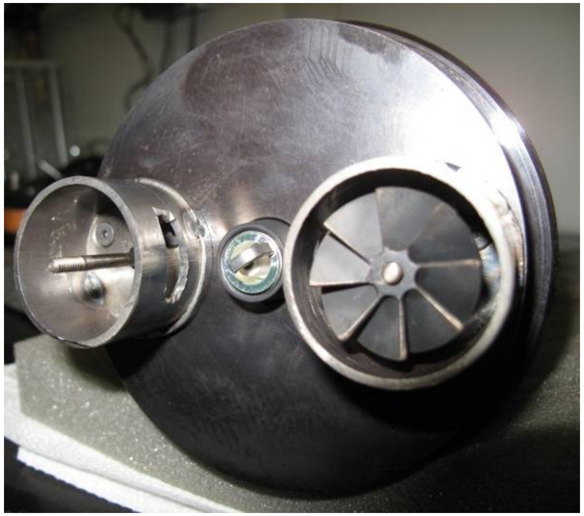
Research and Advanced Engineering

- Combustion Research (MTU)
  - ✓ Progressed all facets of research and development of advanced ignition concepts. Continued development of the high feature combustion pressure vessel, including multiple optical access ports, multiple camera systems, multiple gaseous fuels, dual fans for wide range charge motion, and adapters for production spark plugs; laser-based characterization of vessel revealed need for continued development to represent engine-like conditions.
  - ✓ Completed installation of 3.5L EcoBoost engine and initiated advanced ignition hardware investigations, including ignition energy and phasing, spark plug geometry, and charge motion control.
  - ✓ Completed additional hardware installation and initiated testing on advanced ignition control concepts, including combustion sensing and knock detection. Received and prepared 2nd 3.5L EcoBoost engine for combustion surface temperature measurements.

High Feature Combustion Pressure Vessel

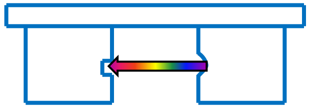
Dual Fans For Wide Range Charge Motion



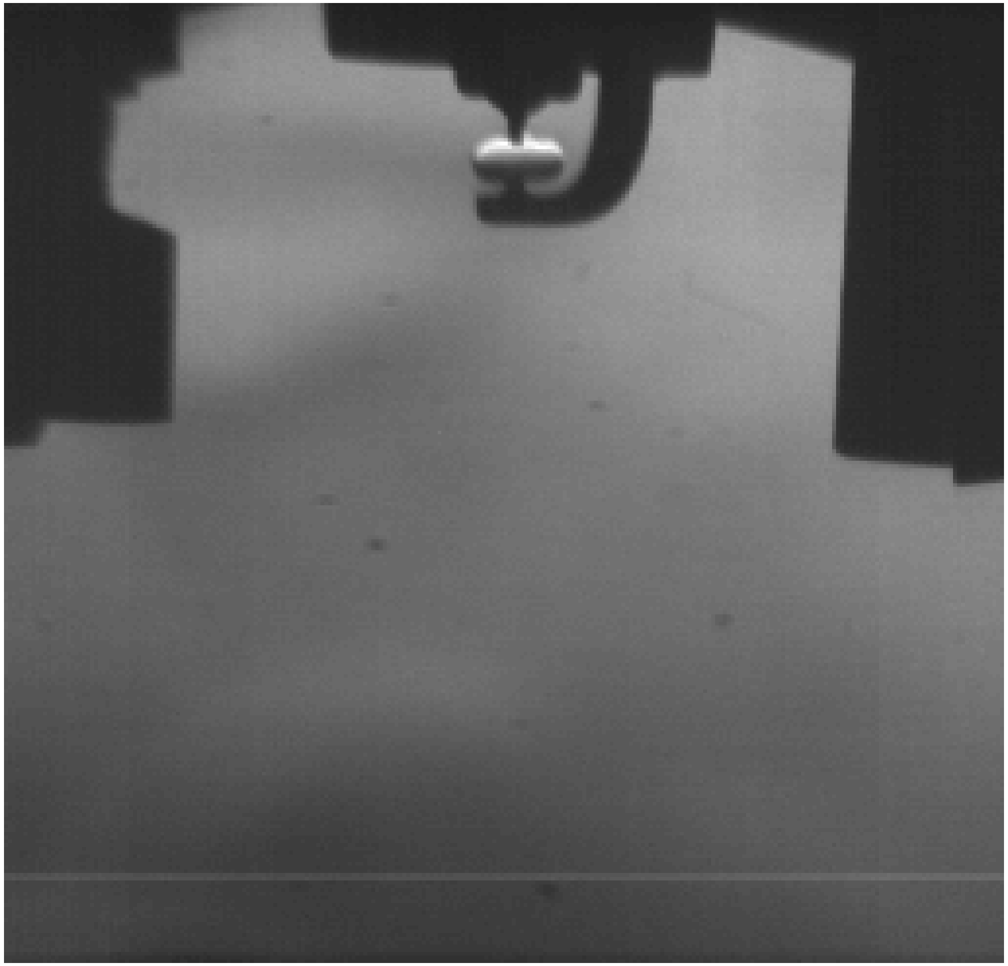


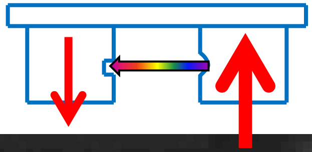
Collaboration

Research and
Advanced Engineering



10% EGR, Φ = 0.6, 13A*2 + 0 us





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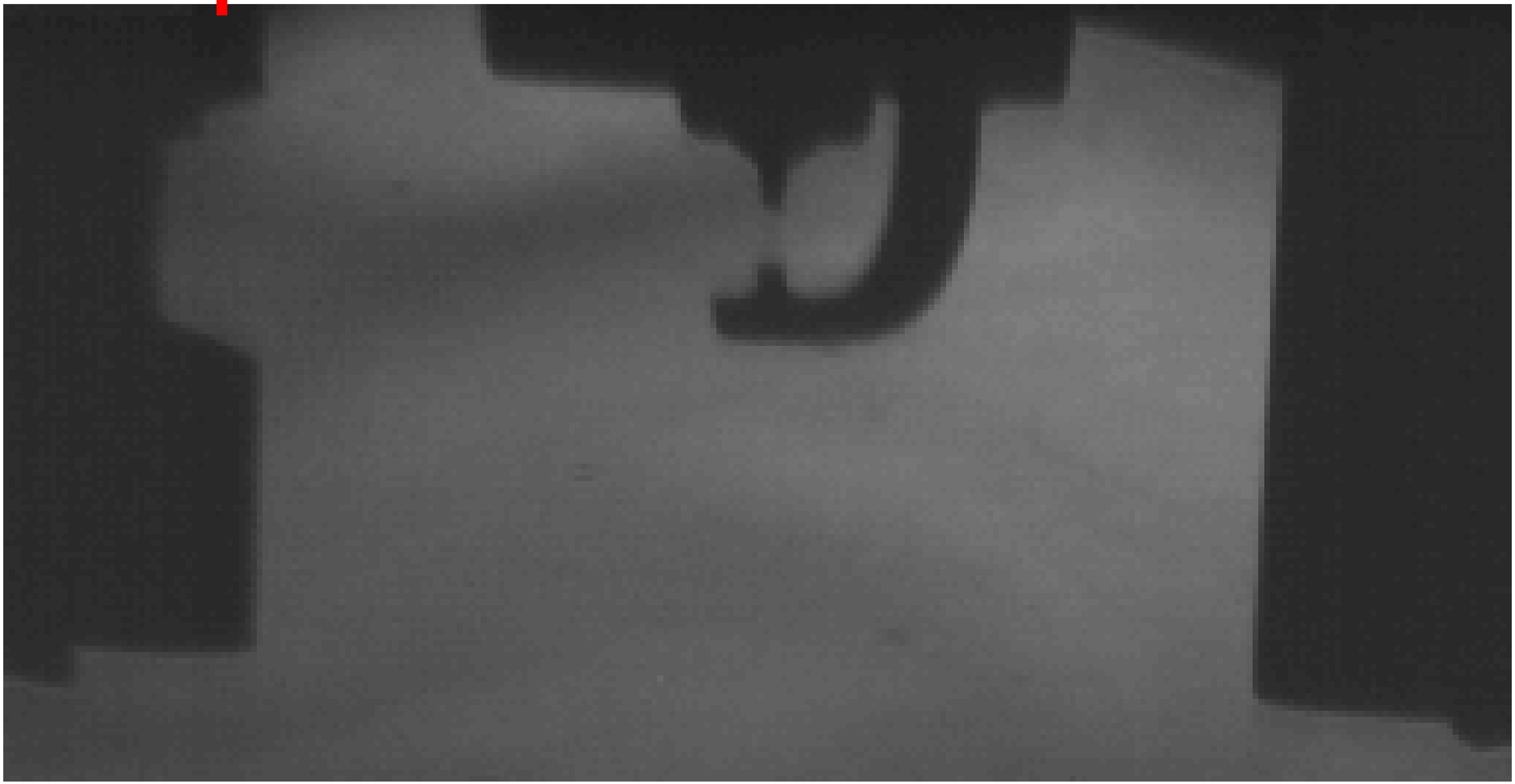

Future Work

- Budget Period 2 – Engine Development 01/01/2012 – 12/31/2012
  - Multi-cylinder development engines completed and dynamometer development started
  - Demonstration vehicle and components available to start build and instrument
  - Project management plan updated

- 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
  - Vehicle build, instrumented, and development work started
  - Aftertreatment system development indicates capability to meet intermediate metrics supporting emissions objectives
  - Project management plan updated

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 and design tasks with material accomplishments to date.
- The outlook for 2012 is stable, with accomplishments anticipated to track the original scope of work and planned tasks, with the exception of milestone "Multi-cylinder development engines design and parts purchased" deferred from 12/31/2011 to 05/01/2012.

Technical Back-Up

Research and
Advanced Engineering

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.		✓