

CHRYSLER

A MultiAir / MultiFuel Approach to Enhancing Engine System Efficiency

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May 18, 2012

2012 DOE Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, Arlington, Virginia

Overview

Timeline

- Project Start Date: May 07, 2010
- Project End Date: April 30, 2013
- Percent Complete: 40%

Barriers

- Downsized engines offer higher fuel economy, but the degree of downsizing is limited by transient performance and dynamic range
- For gasoline engines, abnormal combustion (knock) limits the geometric compression ratio, thereby limiting engine efficiency
- EGR improves engine efficiency, but increases in EGR (and efficiency) are limited by combustion instability
- Engine operation in vehicle is not at its most efficient (ideal) state

Budget

- Total: \$29,992,676
 - Partner Cost Share: \$15,534,104
 - DOE Cost Share: \$14,458,572

Partners

- Argonne National Laboratory
- Bosch
- Delphi
- The Ohio State University

Project Objectives

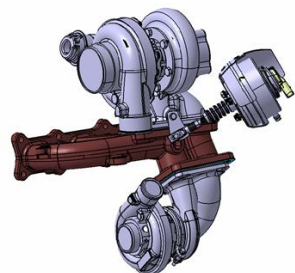
- Demonstrate a 25% improvement in combined City FTP and Highway fuel economy for the Chrysler minivan
 - The baseline (reference) powertrain is the 2009 MY state-of-the-art gasoline port fuel-injected 4.0L V6 equipped with the 6-speed 62TE transmission
 - This fuel economy improvement is intended to be demonstrated while maintaining comparable vehicle performance to the reference engine
 - The tailpipe emissions goal for this demonstration is Tier 2, Bin 2
- Accelerate the development of highly efficient engine and powertrain systems for light-duty vehicles, while meeting future emissions standards
- Create and retain jobs in support of the American Recovery and Reinvestment Act of 2009
- Project content is aimed directly at the listed barriers

Technology Approach & Contribution



Goal $\geq 25\%$ Improvement
in Fuel Economy

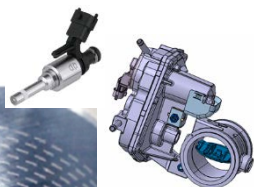
Engine Efficiency



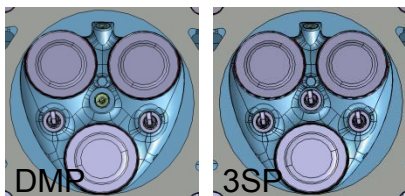
Engine
downsizing,
and 2-stage
boosting



High
compression
ratio

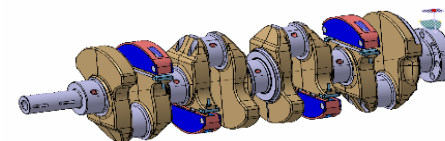


Cooled EGR, DI,
and spray bore
liners for
improved knock
resistance

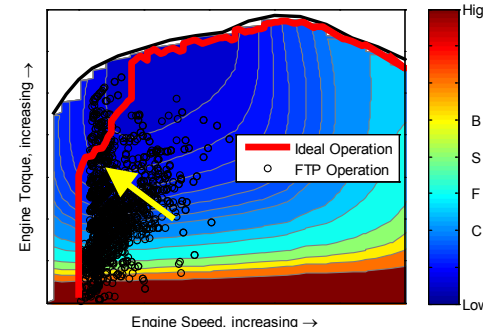


Advanced
ignition for
improved
stability with
high dilution

Low Lock-up Speed



Ideal Engine Operation



45%

21%

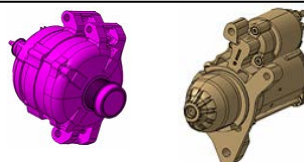
16%

10%

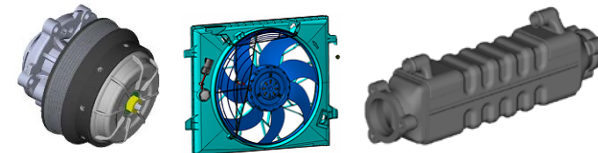
Base
Engine Design
&
Controls

8%

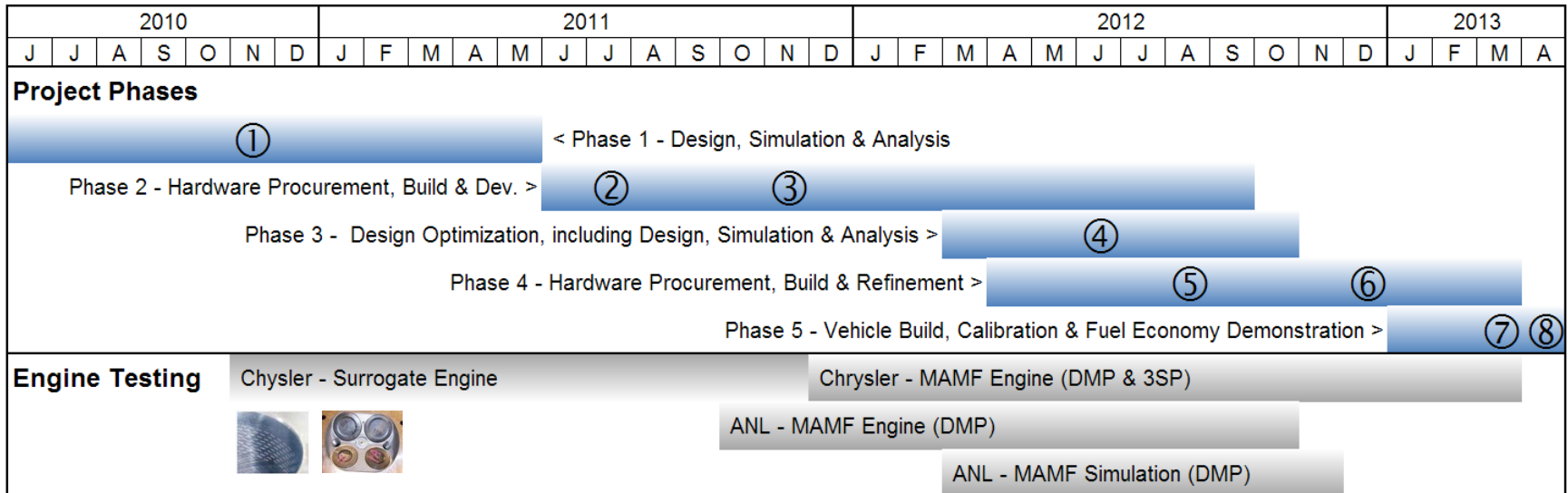
Reduced Losses



Thermal Management



Timeline and Major Milestones

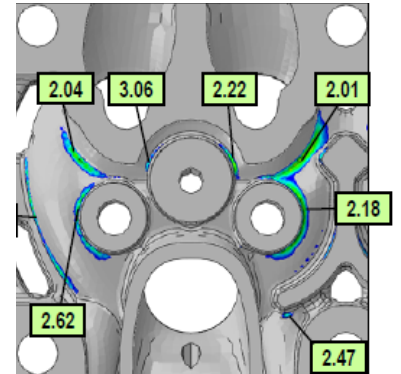


	Month/Year	Milestone or Go/No-Go Decision
①	Completed – November 2010	Performance Specs / Engine Selection
②	Completed – July 2011	Dyno Engine Design Complete
③	Completed – November 2011	Procure, Build & Initial Test of Dyno Engine Complete
④	June 2012	Go/No Go – Dual Fuel for Vehicle Engine
⑤	August 2012	Design Refinement & Procurement Complete – Vehicle Engine
⑥	December 2012	Vehicle Level Controls Complete
⑦	March 2013	Engine Calibration Complete
⑧	April 2013	Vehicle Demonstration

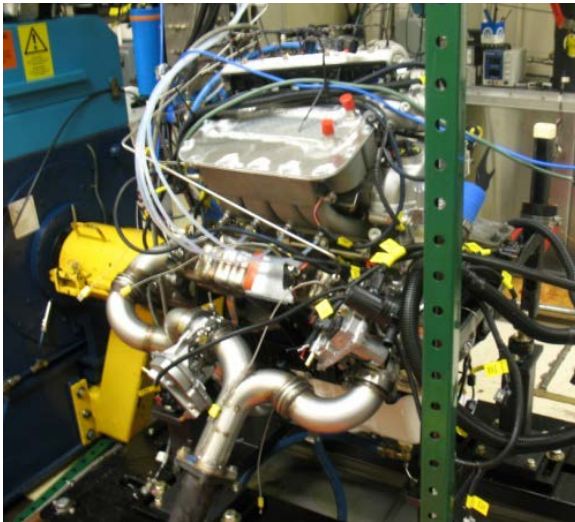
Base Engine Design



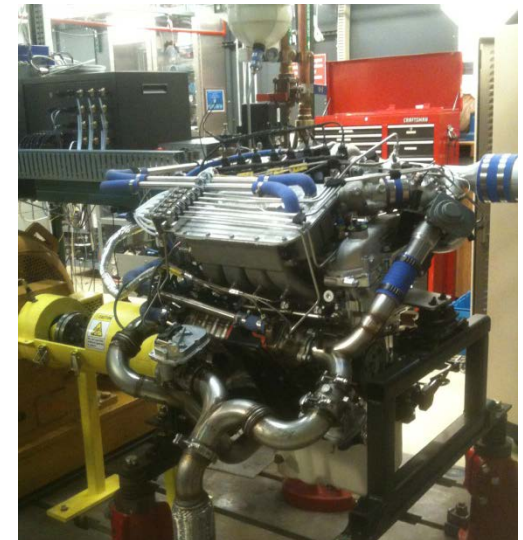
- Production-style analyses using CFD and FEA were performed to determine design and material selection on critical components
- High Cycle Fatigue (HCF) FEA analysis of the cylinder head shows very good safety factors for a peak cylinder pressure of 180 bar
- Engine design was completed for every engine component (3-D Catia files / 2-D prints), and all parts were procured



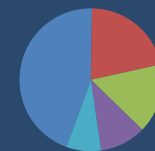
HCF Safety Factors for MAMF
(goal ≥ 1.5)



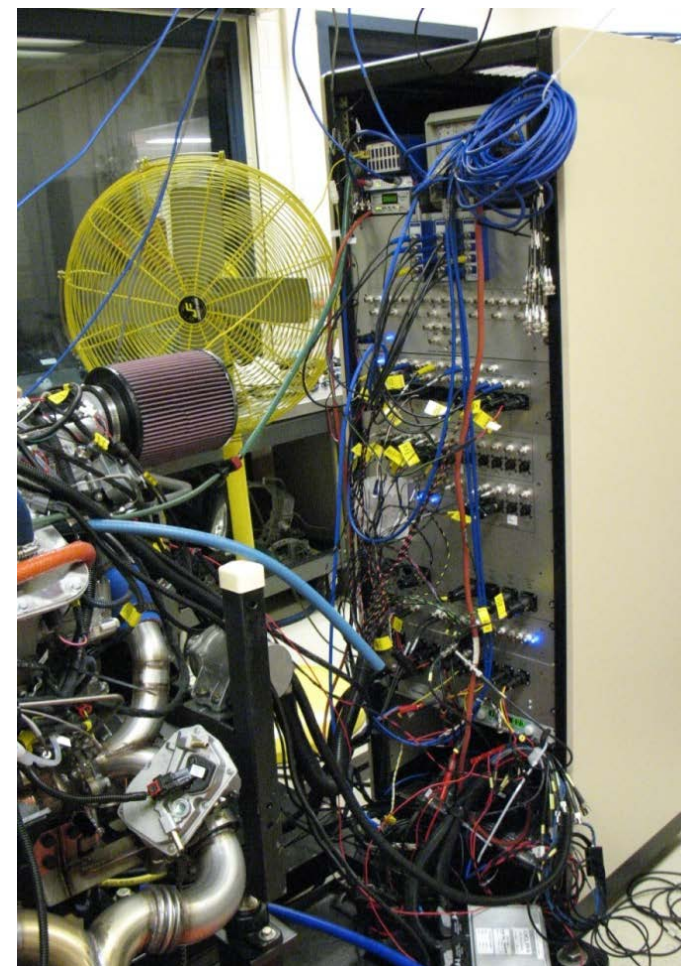
Three (3) engines were assembled and are on test, two at Chrysler (←) and one at Argonne National Lab (→)



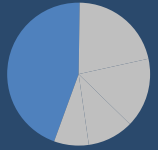
Combustion Controls



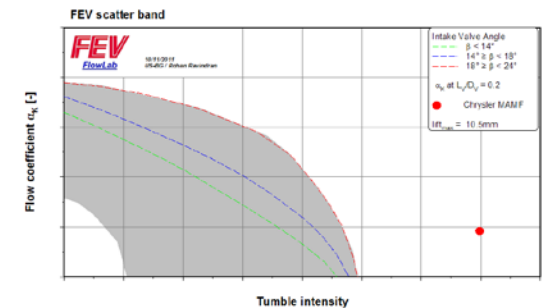
- Dyno engine control system has been completed, and incorporates:
 - Chrysler controller master
 - Bosch GDI slave controller
 - Bosch diesel slave controller
 - Delphi combustion feedback controller
- Coordinated by INTECRIO Rapid Prototype Controller
- Controls development progress:
 - GT Power model used as plant model in co-simulation with Matlab Simulink control system to develop boost control system algorithm
 - Developed closed loop control of Cooled EGR (CEGR)
 - Investigating behavior of dual fuel system in response to actuator set points to support algorithm development



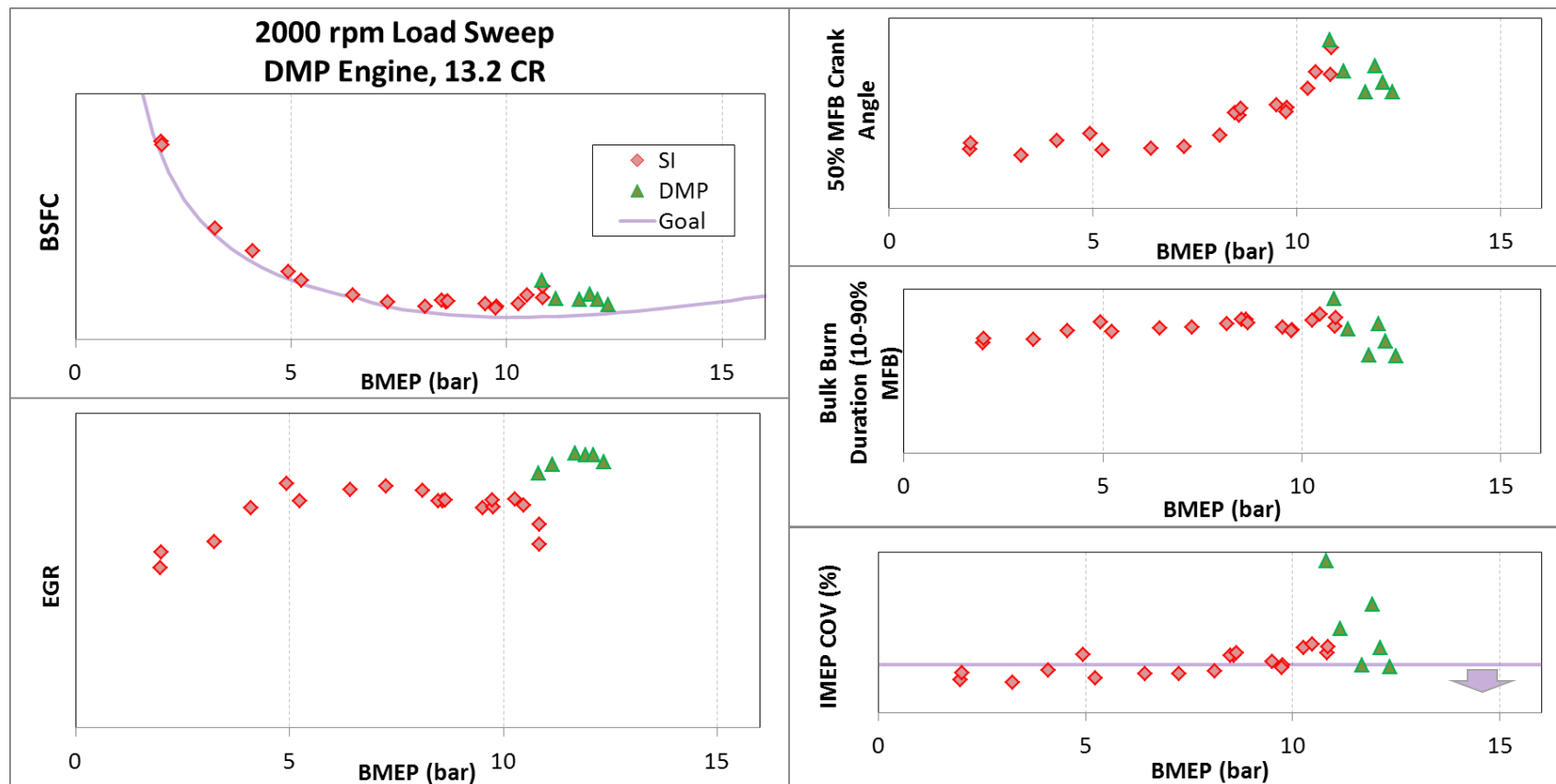
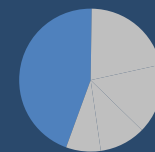
Combustion Approach



- Prevent knock to enable a high geometric compression ratio with good combustion phasing
 - Cooled EGR
 - Gasoline Direct Injection
 - Spray Bore Liner
- Combustion system designed to tolerate high rate of EGR with good combustion stability
 - Very high charge motion intake port and chamber
 - High energy ignition system, dual path using two engines:
 - Diesel injector for Diesel Micro Pilot (DMP) ignition at medium to high load, and two spark plugs per cylinder for light to medium load, with 13:1 compression ratio
 - Three spark plugs per cylinder, 11:1 compression ratio
 - 3 valves per cylinder to provide packaging room for spark plugs and injectors
- Boosted using two turbochargers
 - Series sequential arrangement for improved transient response and boost throughout the engine speed range

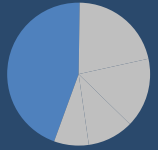


Dyno Engine Results – Dual Fuel Engine



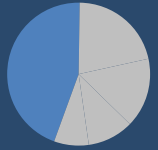
- At 13:1 CR, robust DMP combustion is key to meeting full load goal
- DMP extends load range, improves burn rate and combustion phasing
- Fuel consumption is at goal at low to mid load, within 5% at high load
- Switching between SI and DMP modes is problematic

Dual Fuel Combustion (1 of 2)



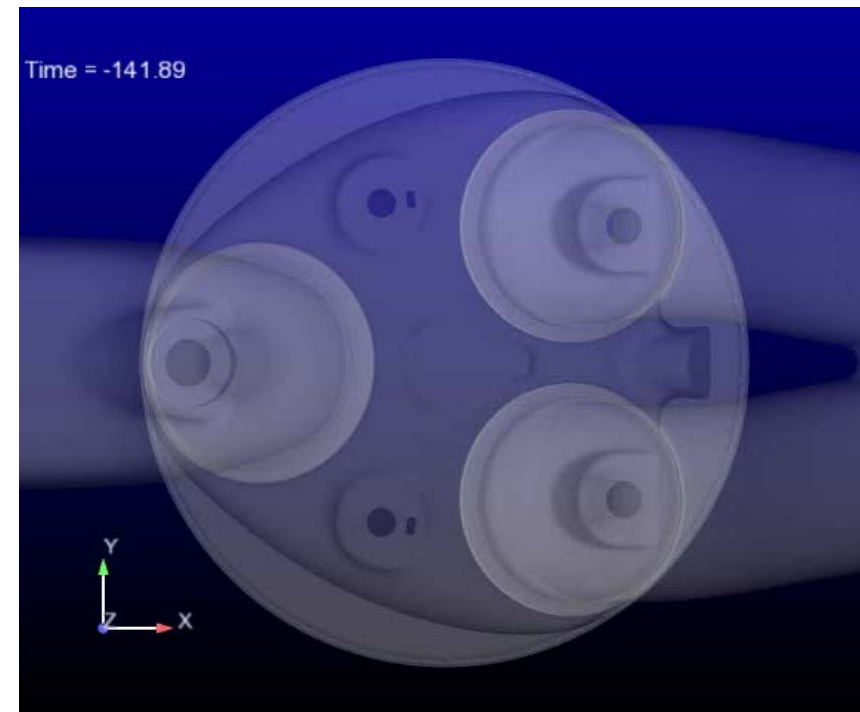
- Controlling the engine over a wide speed/load range while running Diesel Micro Pilot ignition is extraordinarily complicated
- Everything that impacts in cylinder pressure, temperature, and chemistry impacts combustion phasing:
 - EGR rate
 - Intake manifold pressure
 - Intake manifold charge temperature
 - Intake cam position
 - Exhaust cam position
 - Diesel injection pressure
 - Diesel injection timing
 - Diesel injection quantity
 - Coolant temperature
- Argonne National Laboratory is collaborating with Chrysler to better understand DMP combustion through a combination of experimental and computational activities
- Dual fuel decision date is June for the vehicle engine
 - Decision Criteria: Fuel consumption improvement is compelling
 - Emissions penalty is small
 - Automatic steady state and transient control is robust

Dual Fuel Combustion (2 of 2)



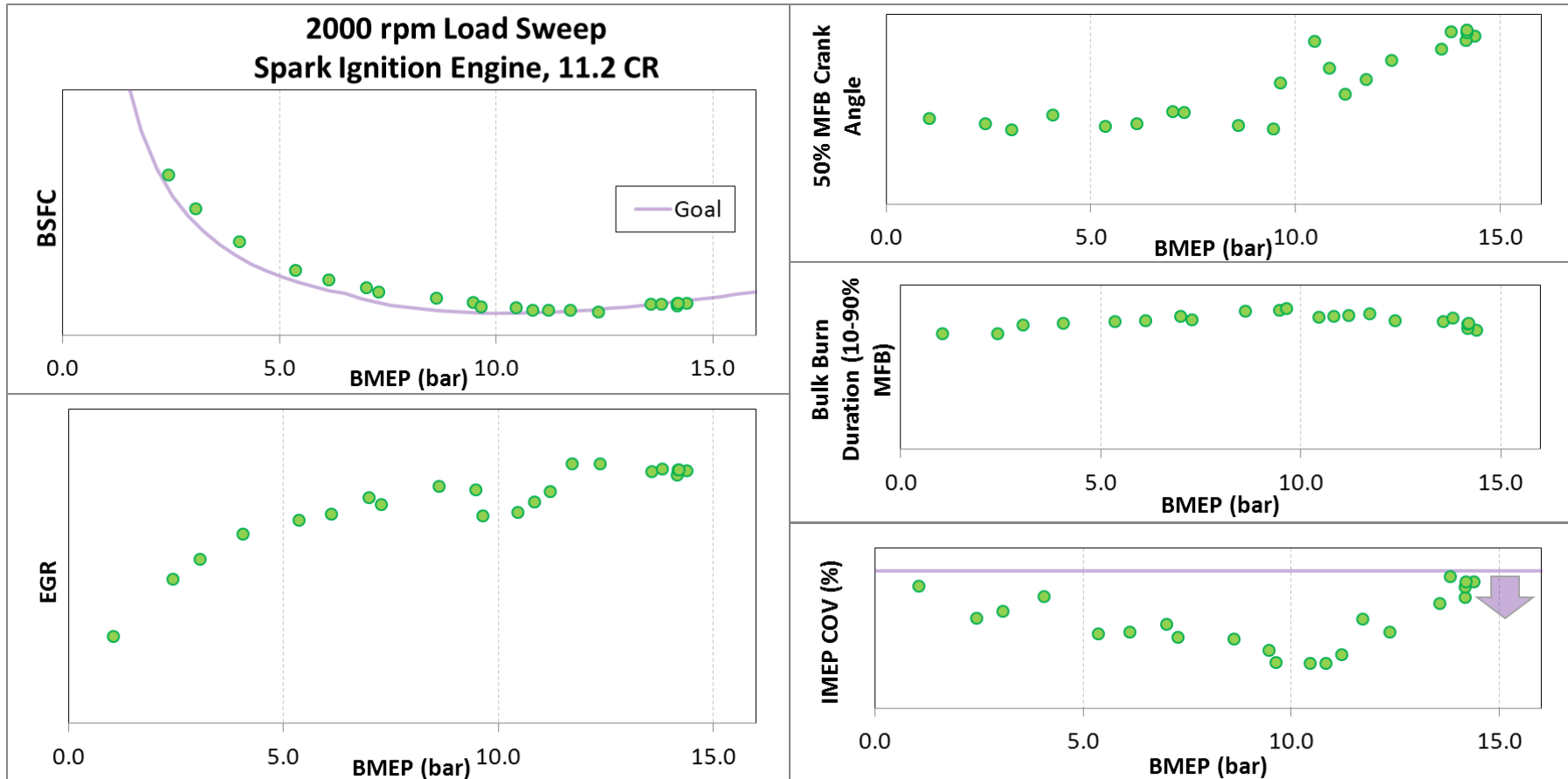
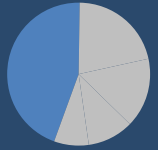
- Combustion modeling at Argonne National Laboratory (ANL)
 - 3D software evaluation was completed, selection was made, and software was procured and installed at Chrysler and ANL
 - Simulation plan has been developed, and ANL contract is in place (work started 3/2012)
 - Computational Resources:
 - 2 simulation specialists
 - 240 solver cores from TRACC cluster
 - Used to explore actuator control to determine lowest fuel consumption strategy and help establish control strategy and algorithm, with GT Power providing the boundary conditions
 - Injector spray tests in APS to validate spray models
 - Simulation results will be compared to in-cylinder imaging from dyno engine at ANL

Combustion Simulation Results: DMP Ignition
> 2000 K Iso-Temperature Volume
2000 rpm / 12 bar BMEP



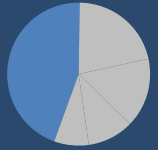
Example of Initial DMP Results

Dyno Engine Results – Single Fuel Engine

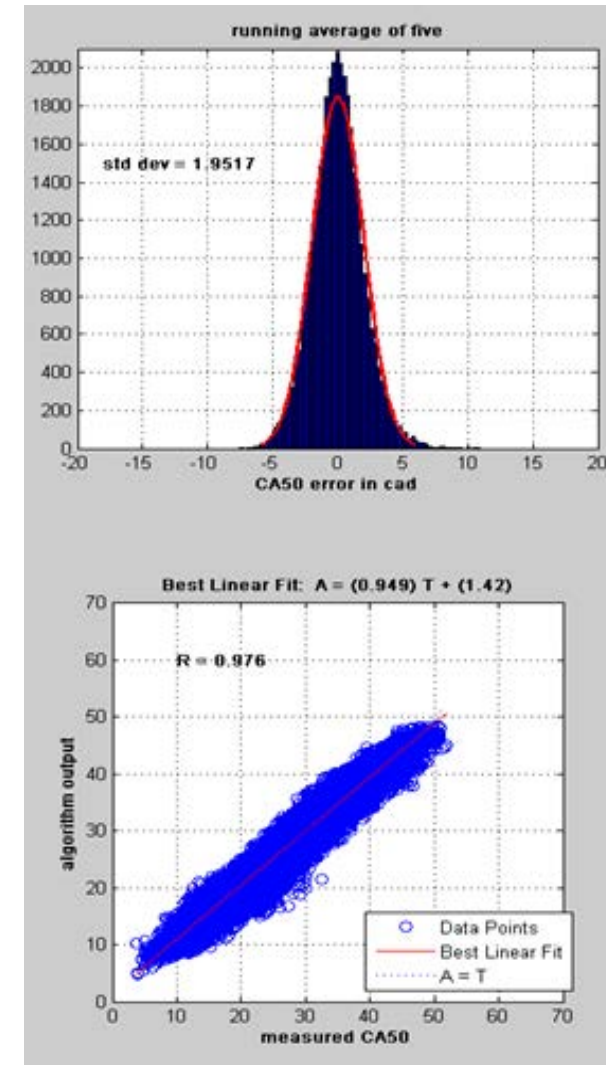


- Single fuel engine (with 3 spark plugs) has a lower CR than the dual fuel engine
- Fuel consumption within 3% of goal at 2000 rpm
- Combustion stability (IMEP COV) is better than goal

Combustion Feedback and Control



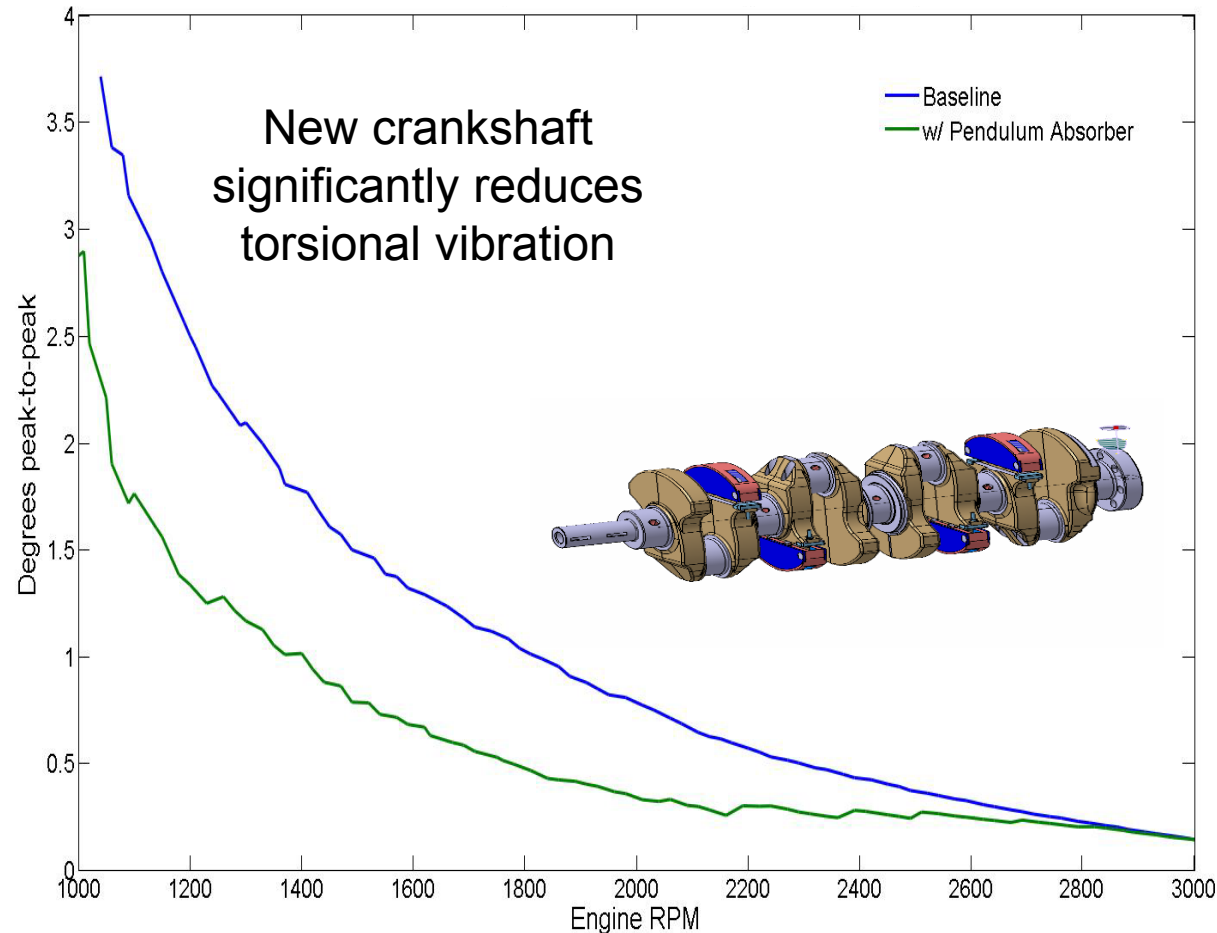
- Delphi Ion-Sense combustion feedback
 - Delphi Ion-Sense-Enabled High Energy Ignition Coil Technology successfully used to extract ion current signature from the combustion process, including during dual fuel operation on Proof-of-Concept engine
 - Algorithms developed to process the ion current signature into derived combustion phasing parameters; standard deviation for 50% MFB correlation is less than 2 degrees
 - Integration of Delphi controller into dyno cell arrangement complete, and communication of Delphi controller with Chrysler Engine Control Unit verified
- Dyno engine includes production-type cylinder pressure sensor which could be used with Delphi controller if necessary
- Engine control strategy under development to incorporate combustion phasing, combustion stability, and knock feedback into Chrysler engine controls



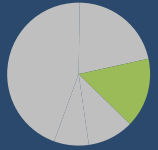
2nd Order Mitigation

- 2nd order mitigation is an enabler for lower torque converter lock-up speeds, and higher engine efficiency
- A Proof-of-Concept pendulum absorber crankshaft (shown) was built and tested in a surrogate vehicle
- Testing of the surrogate vehicle showed a significant reduction in 2nd order crankshaft vibration (see graph), closely matching the prediction
- Other NVH issues were discovered and are being addressed with design improvements

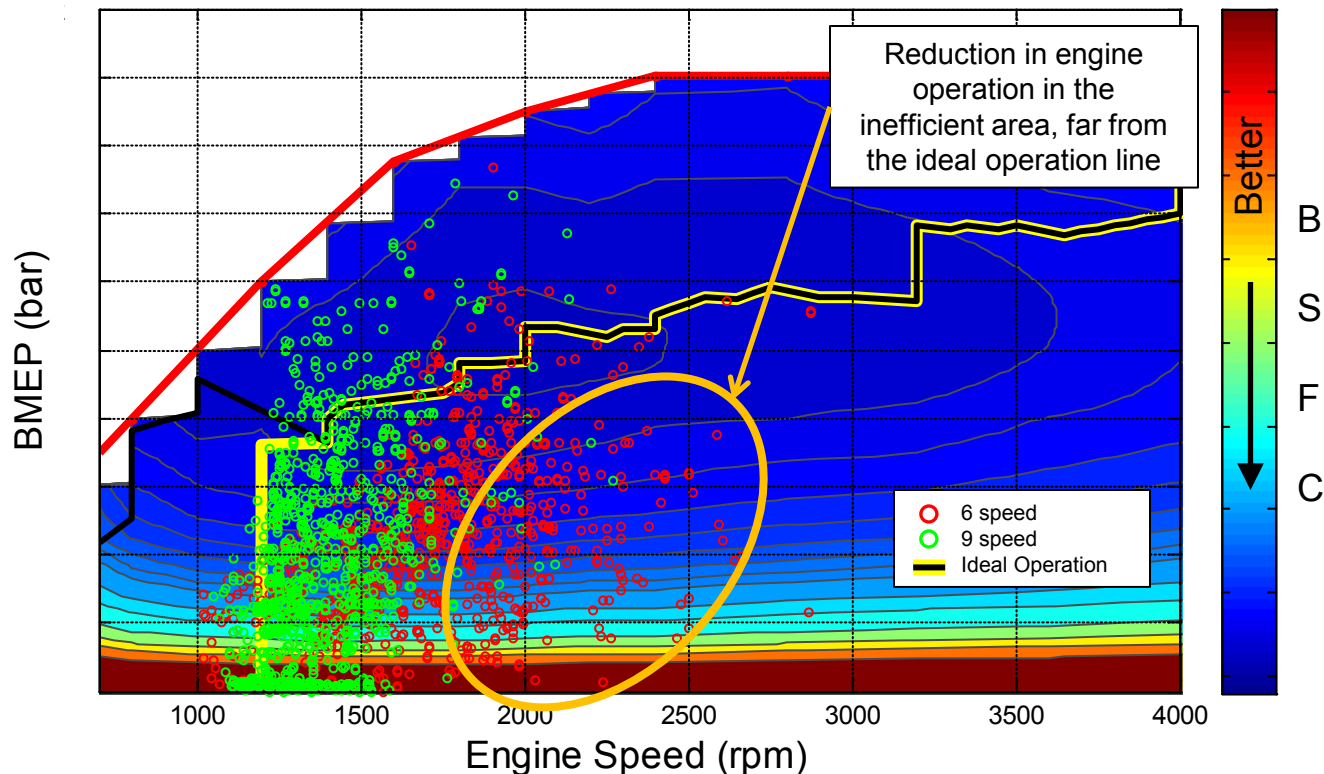
Reduction in 2nd Order Torsional Vibration at Full Load



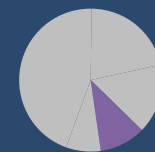
Approaching Ideal Engine Operation



- 9-speed transmission replaces 6-speed transmission
(9 speed transmission development not funded by this project)
- Higher ratio range, and lower ratio steps of 9-speed allows engine to operate closer to the ideal state (minimum fuel consumption for a desired power request)



Thermal Management System (TMS)



• Approach

- Higher steady state temperatures of fluids reduces friction losses
- Faster warm-up of engine & transmission improves mechanical efficiency
- Dual mode coolant pump is used for improved efficiency and control
 - Electric drive → flow on demand
 - Mech. drive → efficiency @ hi speed

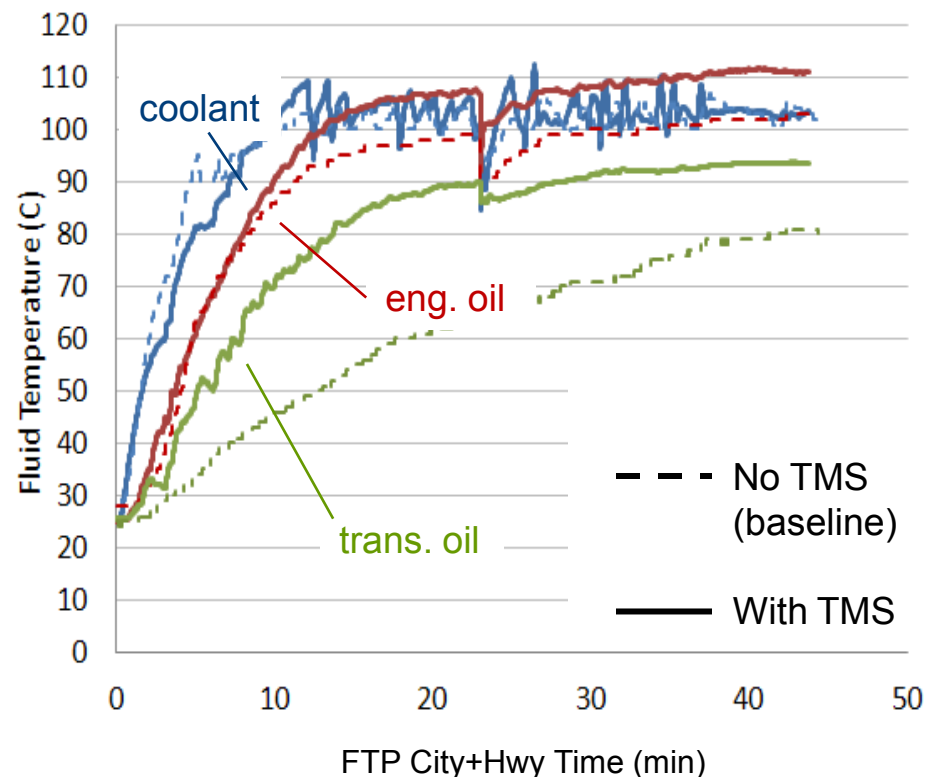
• Accomplishments

- Thermal management system evaluated on surrogate vehicle
 - Demonstrated %FE improvement
 - Validated thermal prediction model
 - Validated thermal function of controls model (from OSU)
- Coolant circuit flow stand built / tested to:
 - Develop coolant pump control strategy
 - Validate 1D fluid circuit model

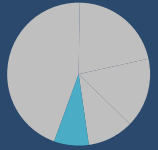
Fluid Temperature Benefit On Surrogate Vehicle and Powertrain

No TMS = Baseline

With TMS = 3.0% MPG improvement

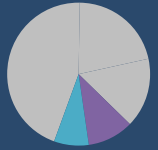


Reduced Losses (Fuel Shut Off, Stop/Start & Ancillary Load Reduction)

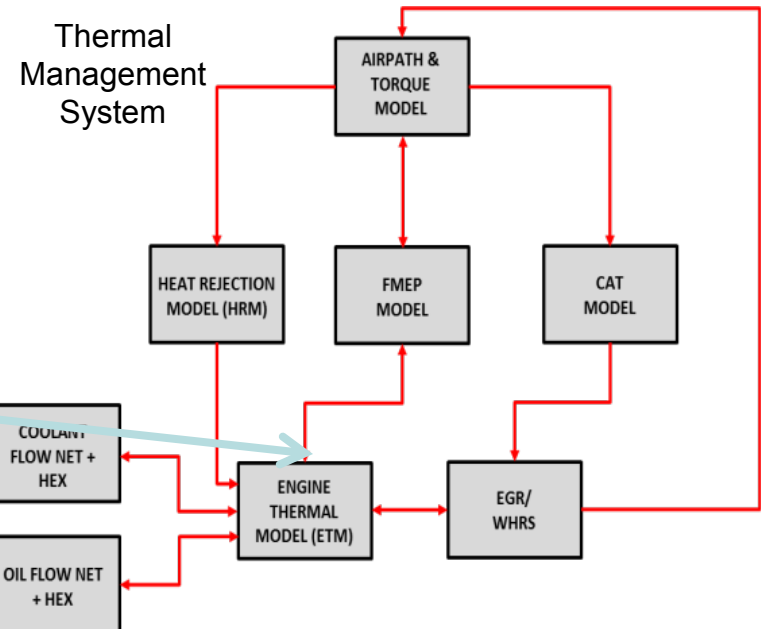
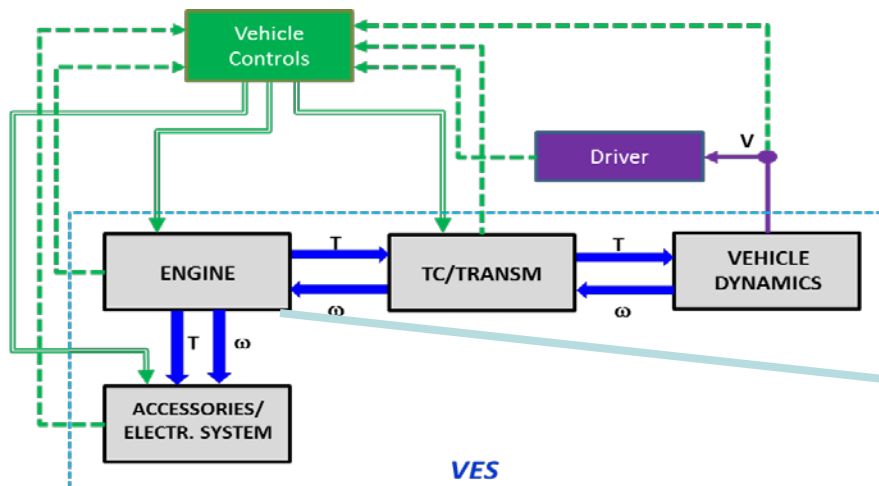


- Fuel Shut Off - Software created & operational with 9-speed transmission
- Stop/Start - Software interface for 9-speed transmission defined
 - Hardware and interfaces defined for Stop/Start
- Enhanced Voltage Regulation (EVR) algorithm strategy prototyped
 - Closed loop control of charging parameters
 - Opportunistic control algorithm for deciding when to charge (and when not to)
 - Will be integrated into overarching control scheme being developed by OSU, which manages the ancillary loads in the most efficient way possible
- EVR + Stop/Start
 - Delay charging the battery (energy payback for the stop/start event) until there is a more efficient time to charge
 - Significantly improves the cycle fuels savings, as opposed to charging the battery immediately after start

Controls for TMS and Reduced Losses



- OSU developed a comprehensive Vehicle Energy Simulator (VES) tool to analyze vehicle ancillary loads and thermal system components
 - Predicts energy utilization/consumption for each of the main vehicle subsystems
 - Provides vehicle fuel economy prediction for a given driving schedule
- VES verified and being used to develop control system architecture and algorithms



Partnerships / Collaborations



Providing computational fluid dynamics (CFD) modeling, spray measurements, and in-cylinder combustion high-speed imaging to support combustion development and control



Supplied fuel injectors, lines, pumps, harnesses and controllers for the DI gasoline and DI diesel fuel systems, and collaborated with Chrysler to integrate the injector drivers



Supplied Ion Sense coils and developing combustion feedback system to allow closed loop combustion control



Developed Vehicle Energy Simulation (VES) and developing supervisory controller (Vehicle Energy Manager – VEM) that oversees and integrates energy management of vehicle subsystems

Future Work / Summary

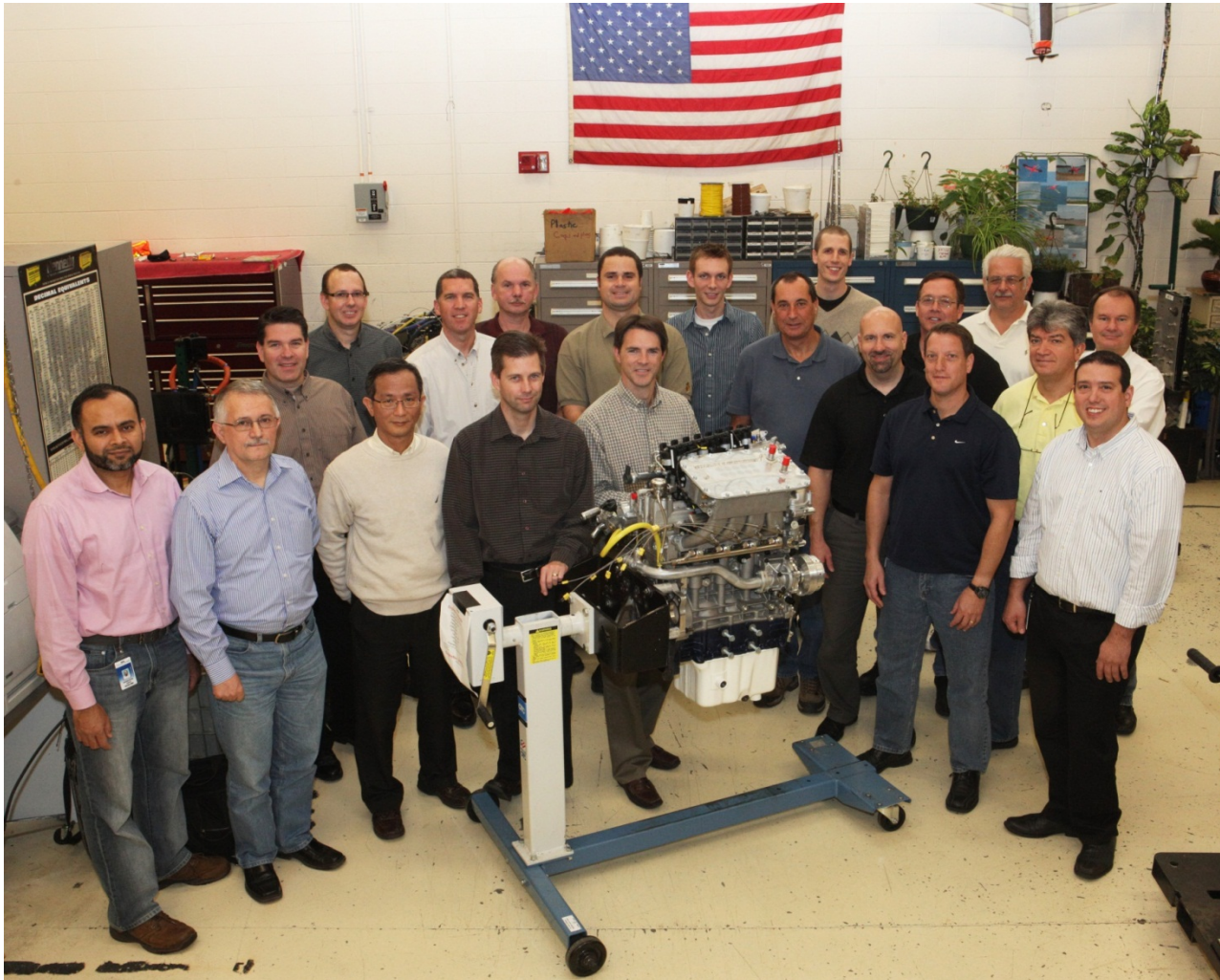
- Future Work

- Complete dynamometer engine testing and model correlation
- Refine engine design as required to best meet all functional objectives
 - Based upon correlated models and a review of lessons learned from current design/test efforts
- Determine engine type (i.e. single or dual fuel) for vehicle engine
- Complete development and implementation of engine control system
- Build demonstration vehicles and start emissions testing

- Summary

- Engine design is complete, part procured, engines built and on test
- Current modeling and proof-of-concept testing support meeting the 25% fuel economy improvement using the defined technologies
- Challenges exist to effectively control the various technologies to optimize the impact of each in an operating engine
- The focus for the remainder of the project will be to develop the operational strategies and controls to maximize the efficiency of the hardware at hand

Thank You.

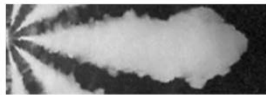


Technical Back-Up Slides

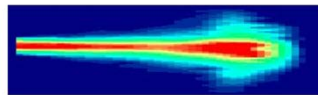
Argonne National Laboratory Spray Measurements

X-rays Reveal Detailed Fuel Distribution

Visible Light Imaging



X-Ray Imaging



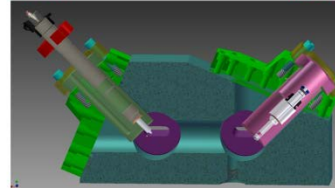
- X-Ray Radiography gives a quantitative measure of the fuel distribution
 - Near-nozzle region of sprays cannot be probed quantitatively with visible light
 - Quantitative data for development and validation of computational models
 - Robust, well-validated technique
- Precise data is critical to Chrysler's combustion strategy
 - Allows more accurate modeling: fuel dispersion vs. time
 - Modeling will be needed to optimize at broad range of operating points



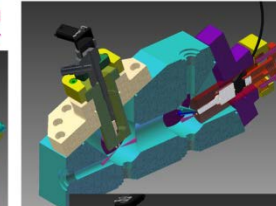
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New Spray Chamber for Multi-Hole Injectors

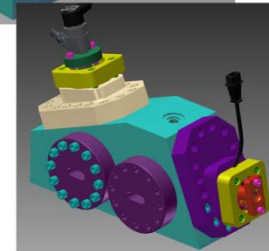
Diesel injector



GDI injector



- Existing spray chambers do not accommodate unique spray angles
- Designed to ASME Pressure Vessel Code
 - FEA modeling of pressure loading
 - Passed division design review
 - X-ray transparent windows complete
- Fabrication complete in April 2012



2

Completed Assembly of Low-Pressure Fuel Delivery System

- Delivers fuels up to 200 bar injection pressure
- Fuel supply for GDI hardware
- Flexible: designed to accommodate a range of fuels: gasoline and diesel
- System shakedown currently underway and will be complete by mid-March



3

Testing Schedule

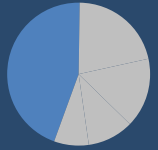
- First x-ray experiments testing GDI system in April 2012
 - Will use new fuel system
 - Will use existing spray chamber at low ambient pressure
 - Test direct injection of gasoline
- Second tests of GDI system in June 2012
 - New spray chamber allows simulation of injection at high-boost conditions
 - Test diesel micro pilot performance using GDI hardware
- Final x-ray measurements in July 2012
 - Tests of diesel micro pilot system
 - High ambient pressure



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4

Emissions



- Emissions control approach:
 - Stoichiometric operation over entire speed/load range
 - Three way catalyst
 - Cold Start Strategy:
 - Secondary air
 - Investigate expansion stroke injection during secondary air injection
 - Turbo control valves open on cold start

