A MultiAir / MultiFuel Approach to Enhancing Engine System Efficiency

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ACE062

Overview

Timeline

- Project Start Date: May 07, 2010
- Project End Date: April 30, 2014
- Percent Complete: 98% (Report Pending)

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

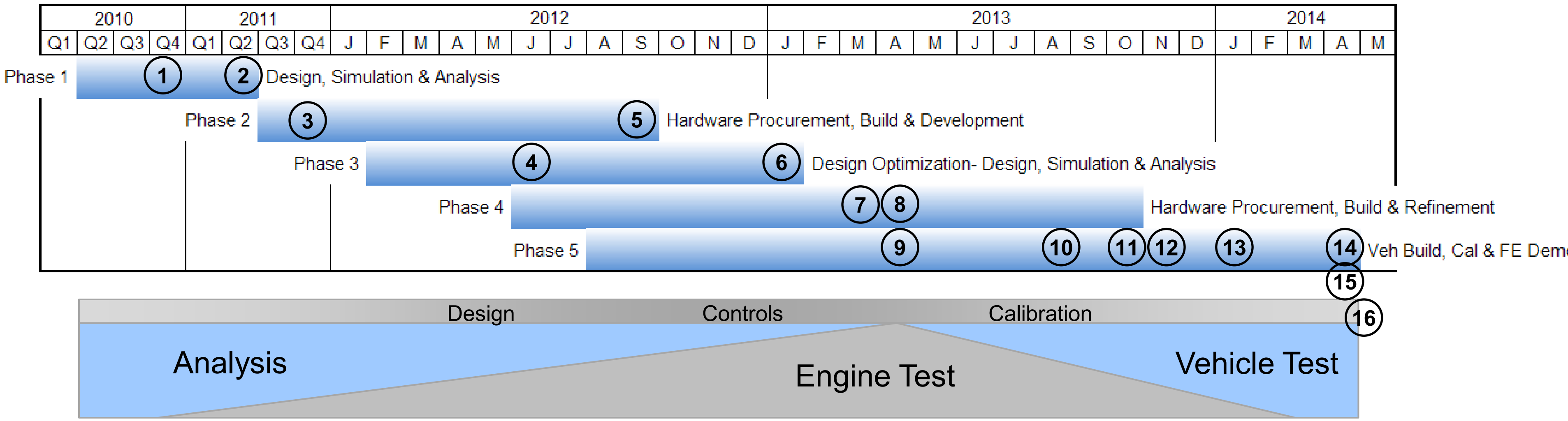
Budget

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

Partners

- Argonne National Laboratory (ANL)
- Bosch
- Delphi
- The Ohio State University (OSU)

Timeline and Major Milestones



#	Date	Milestone
1	Nov 2010	Performance Specs / Engine Selection
2	Jul 2011	Dyno Engine Design
3	Nov 2011	Procure, Build, Initial Test of Dyno Engine
4	Jun 2012	Alpha 2 Engine Technology Selection
5	Sep 2012	Testing Results for Alpha 2 Design Input
6	Jan 2013	Alpha 2 Engine Design
7	Mar 2013	Alpha 2 Engine Procurement
8	Apr 2013	Engine Controls and Vehicle Design

#	Date	Milestone
9	Apr 2013	Alpha 2 Dyno Engine First Fire
10	Aug 2013	Vehicle Energy Simulator (OSU)
11	Oct 2013	Vehicle 1 Build
12	Nov 2013	Engine Dyno Calibration (part load / FTP area)
13	Jan 2014	Vehicle 2 Build
14	Apr 2014	Engine Dyno Calibration (full range / EtOH)
15	Apr 2014	Vehicle Calibration
16	Apr 2014	Vehicle Demonstration

Project Objectives

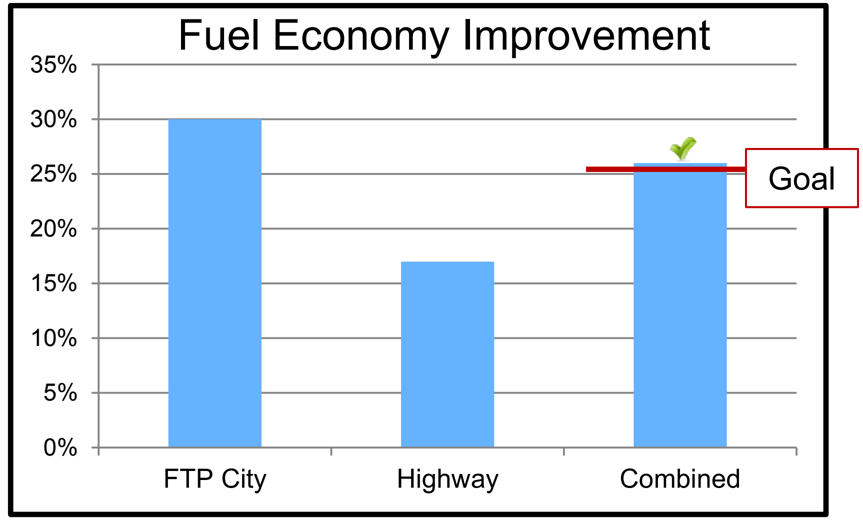
- Demonstrate a 25% improvement in combined City FTP and Highway fuel economy for the Chrysler minivan
  - The baseline (reference) powertrain is the 2009 MY state-of-the-art gasoline port fuel-injected 4.0L V6 equipped with the 6-speed 62TE transmission
  - This fuel economy improvement is intended 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 technologies 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

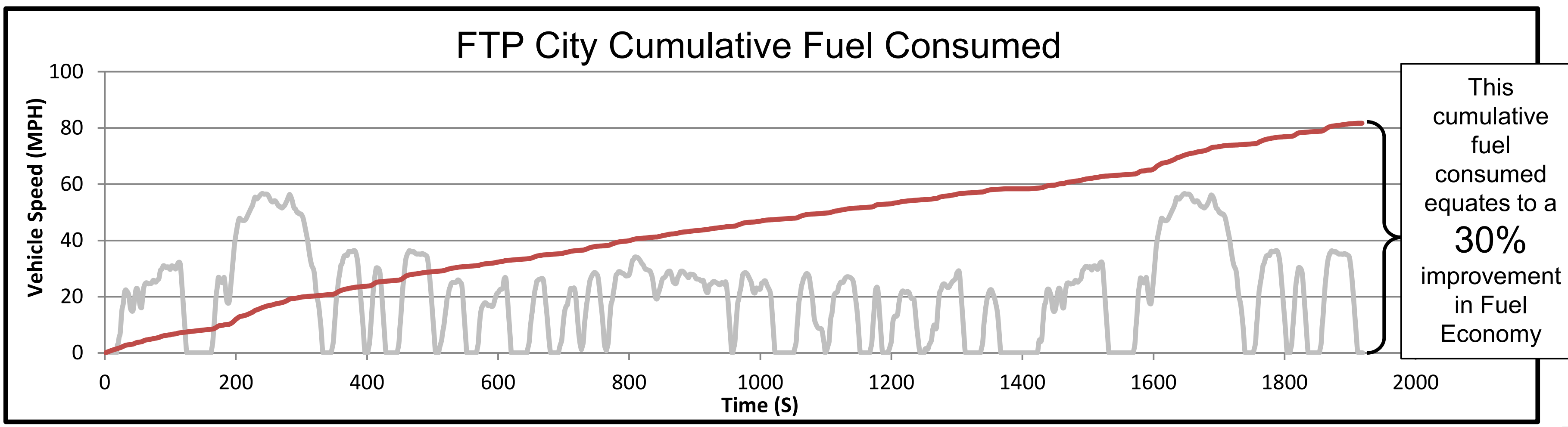
Results – Fuel Economy

Goal = 25% improvement in combined FTP City and Highway fuel economy achieved in Powertrain Test Cell, vehicle results are pending

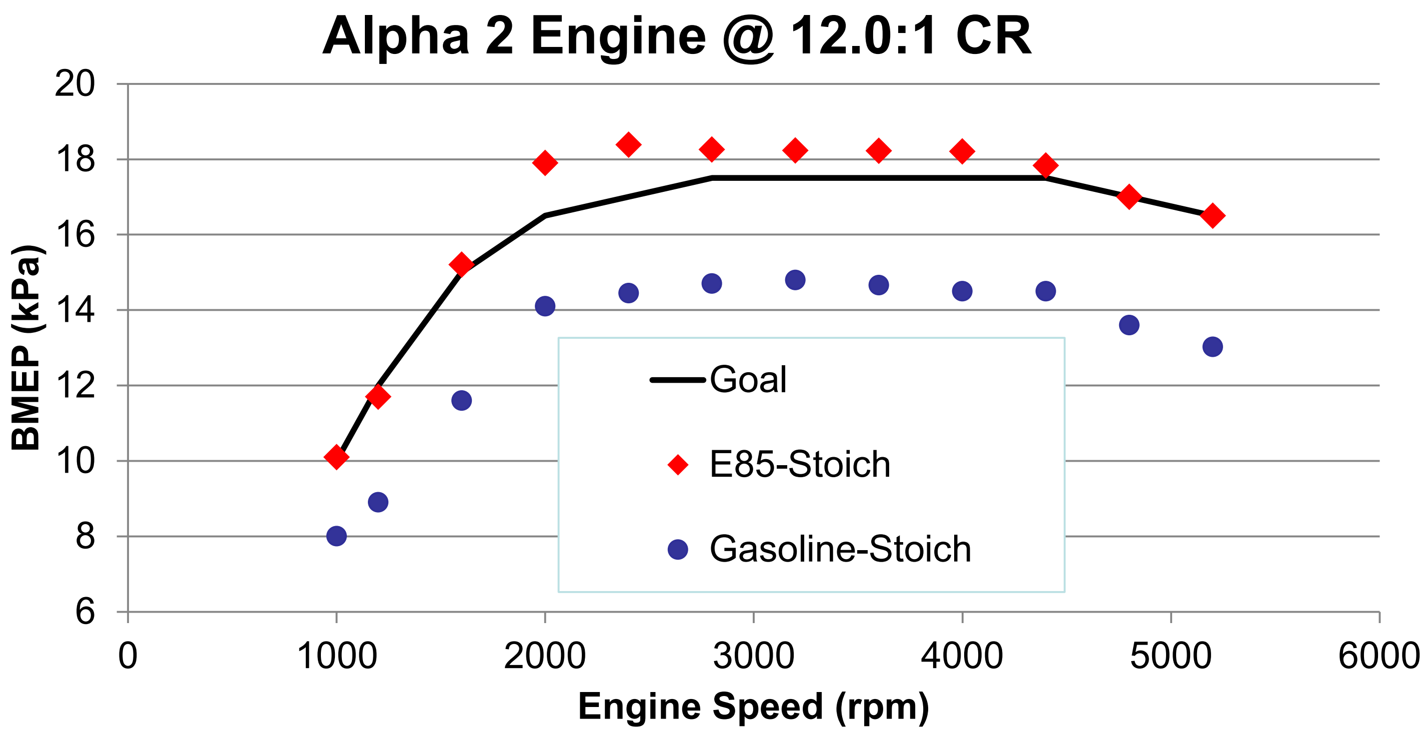
Fuel Economy Improvement

FTP City	Highway	Combined
30%	17%	26% ✔





Results – Performance



Goal = Maintain comparable vehicle performance to the reference engine

Goal Achieved

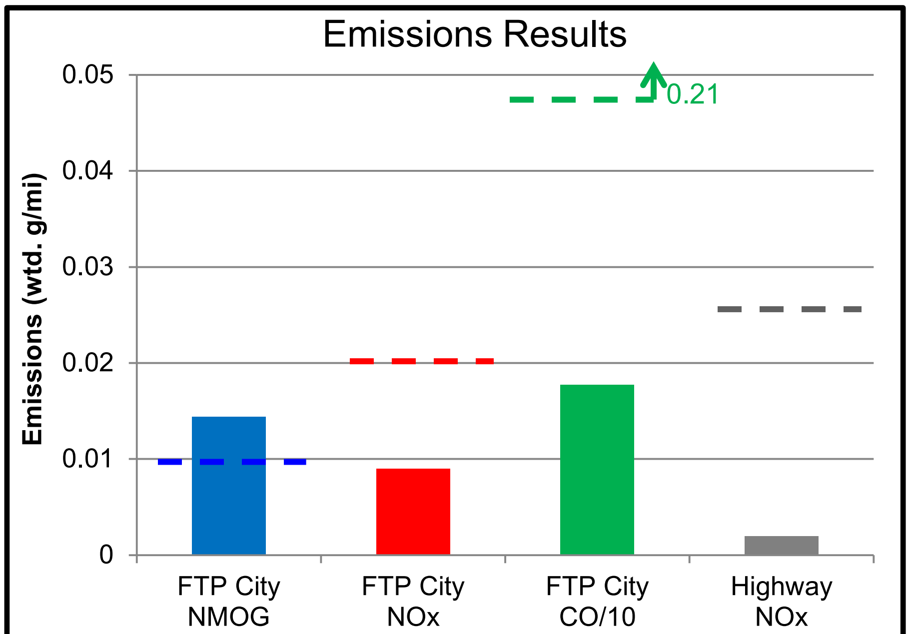
Vehicle Performance	0 to 30 MPH Time (sec)	0 to 60 MPH Time (sec)	1/4 Mile Time (sec)
MAMF 2.4L	3.20	8.73	16.80
4.0L	3.31	8.66	16.77

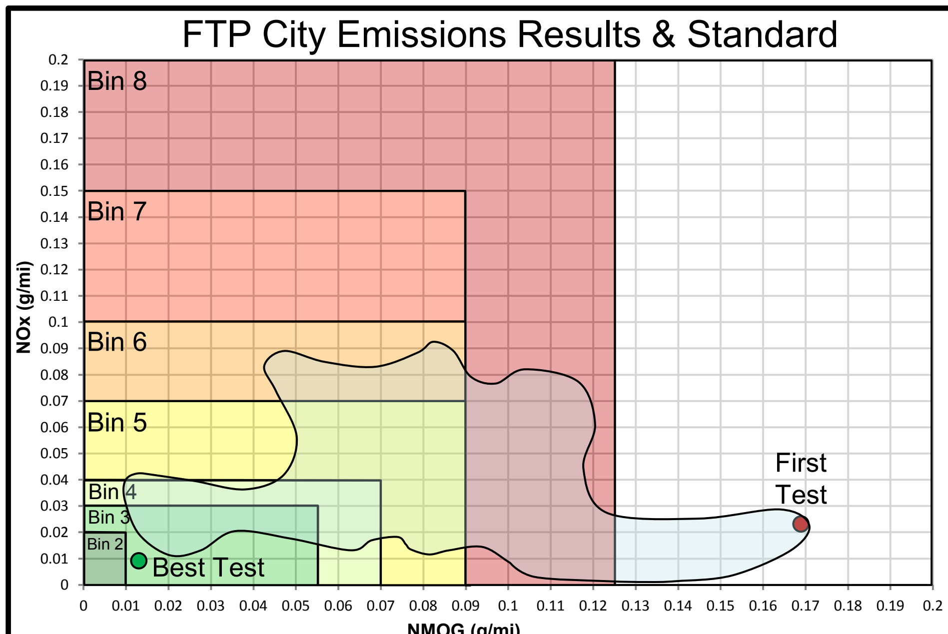
Results – Tailpipe Emissions

	FTP City Cycle			Highway Cycle
Bag Weighted g/mi	NMOG	NOx	CO	NOx
Vehicle Status	0.014	0.009	0.18	0.003
Emission Standard	0.010	0.020	2.10	0.026

Goal = Tailpipe emissions demonstrated at Tier 2, Bin 2

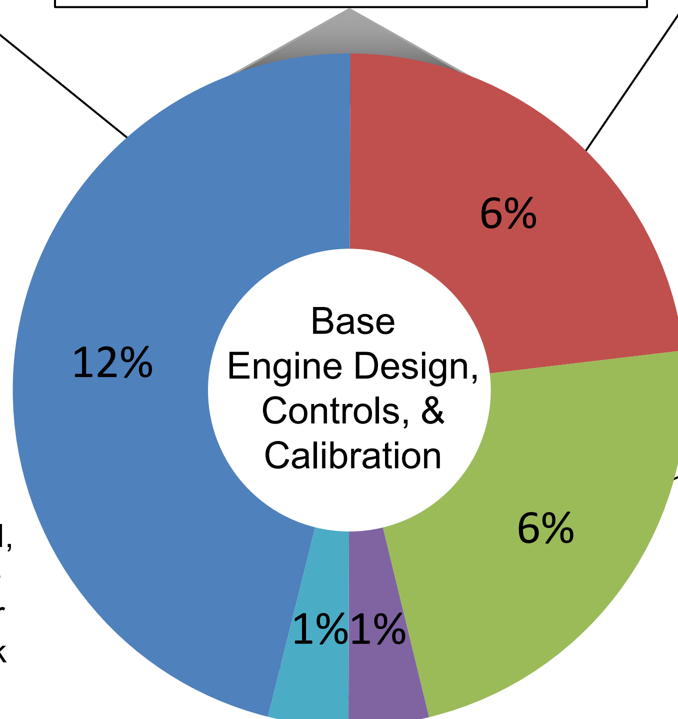
Goal was not yet achieved, but the equivalent Tier 3 standard was





Technology Approach & Contribution

Fuel Economy Improvement = 26%



Engine Efficiency

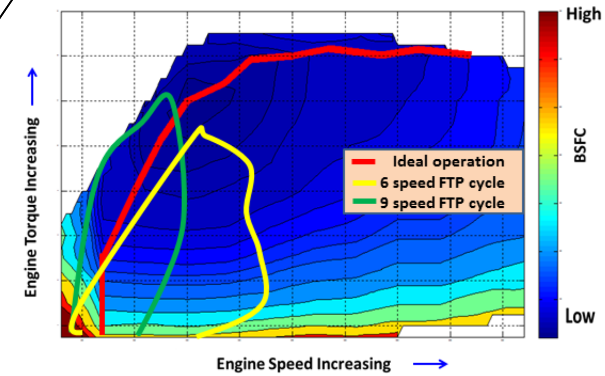
Engine downsizing, and 2-stage boosting

High compression ratio

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

Advanced ignition for improved stability with high dilution

Ideal Engine Operation



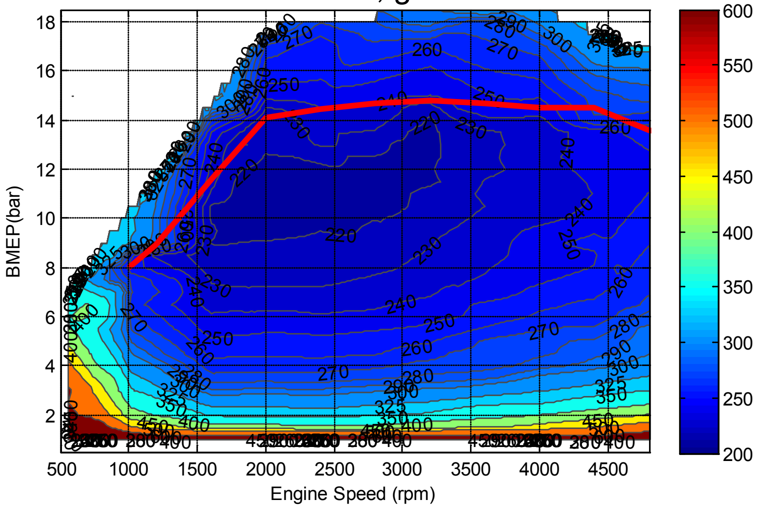
Low Lock-up Speed

Reduced Losses

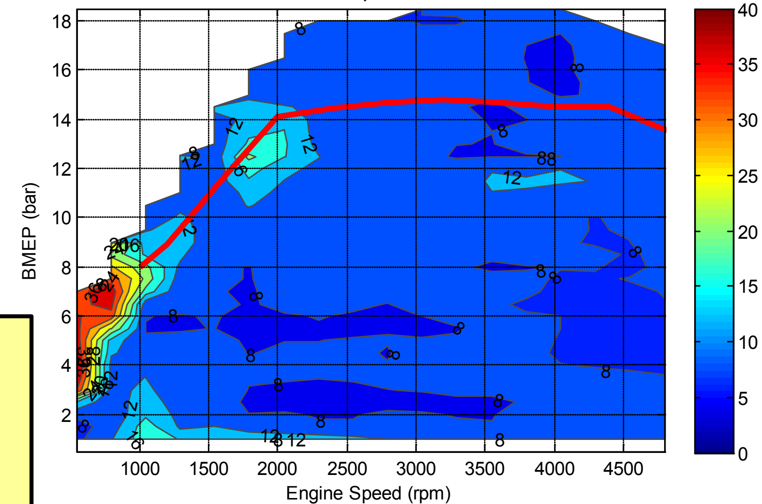
Thermal Management

Engine Efficiency

BSFC, g/kWh



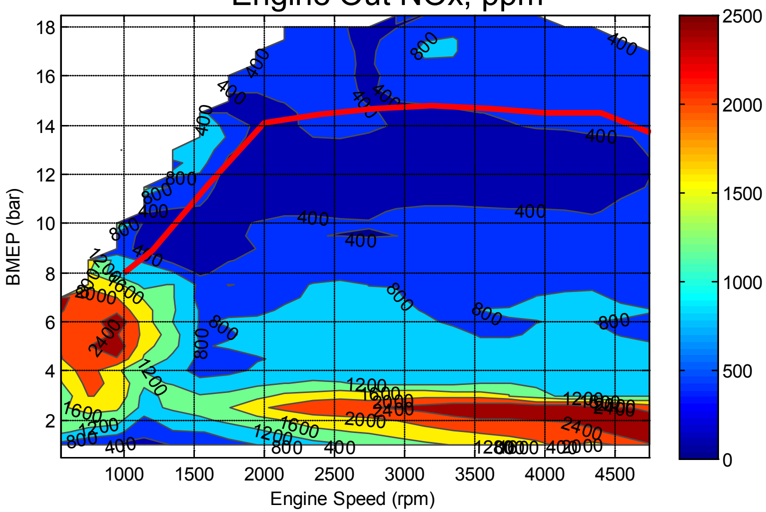
CA50, °ATDC



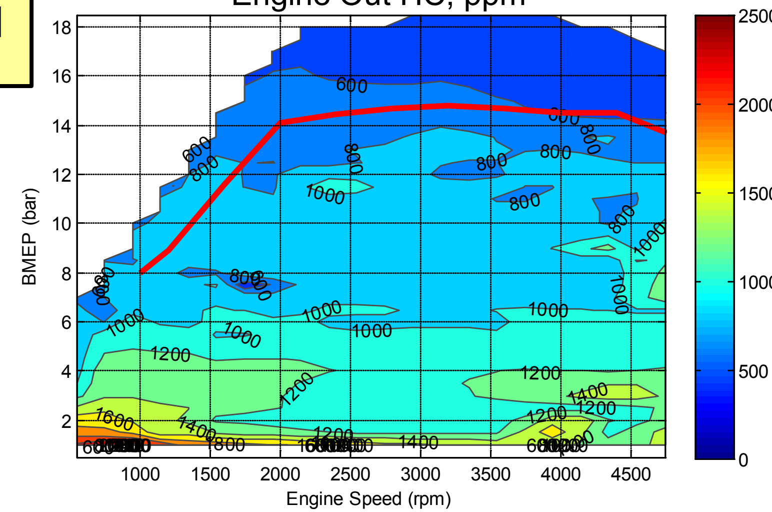
Gasoline Only &

Full-Range Lambda = 1

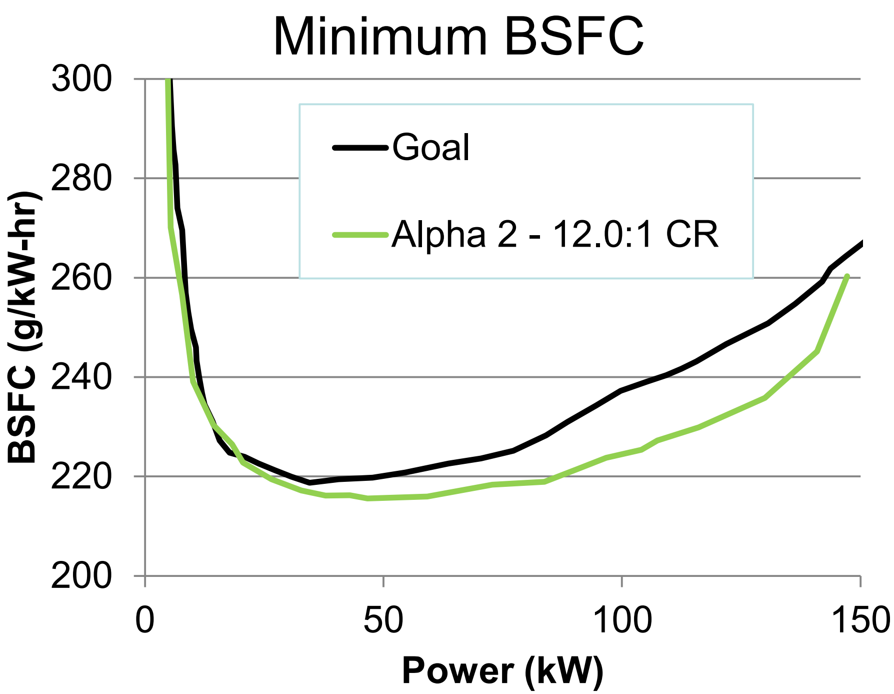
Engine Out NOx, ppm



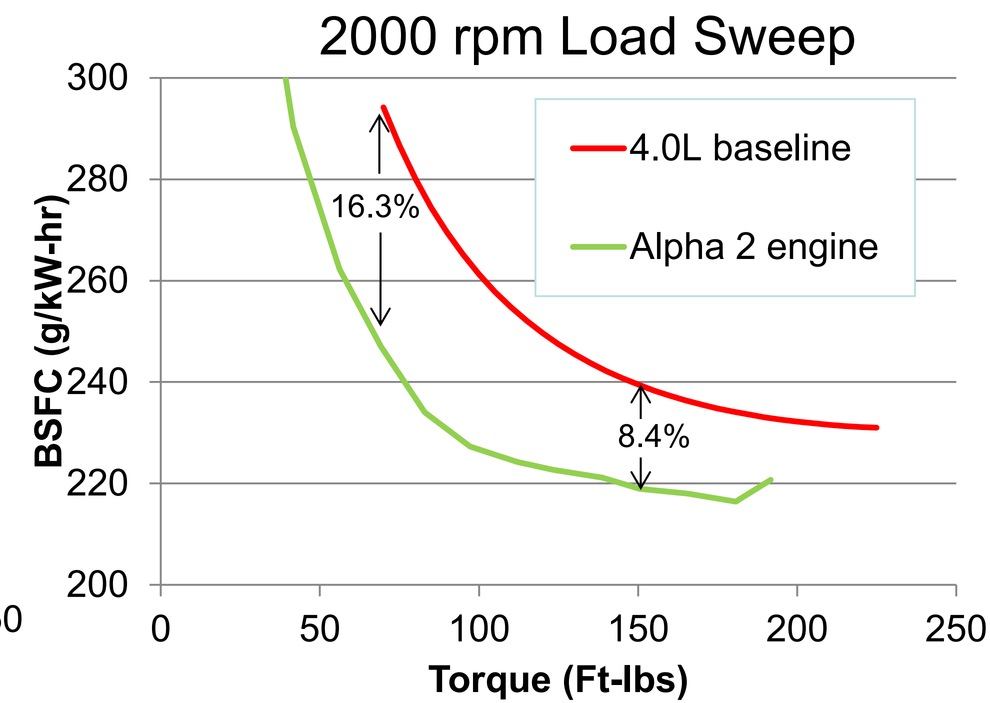
Engine Out HC, ppm



Engine Efficiency



The Alpha 2 engine fuel consumption is at or below goal throughout the load range



The Alpha 2 engine fuel consumption is well below the 4.0L at a given torque

Engine efficiency alone yields a 12% Fuel Economy improvement (combined cycle)

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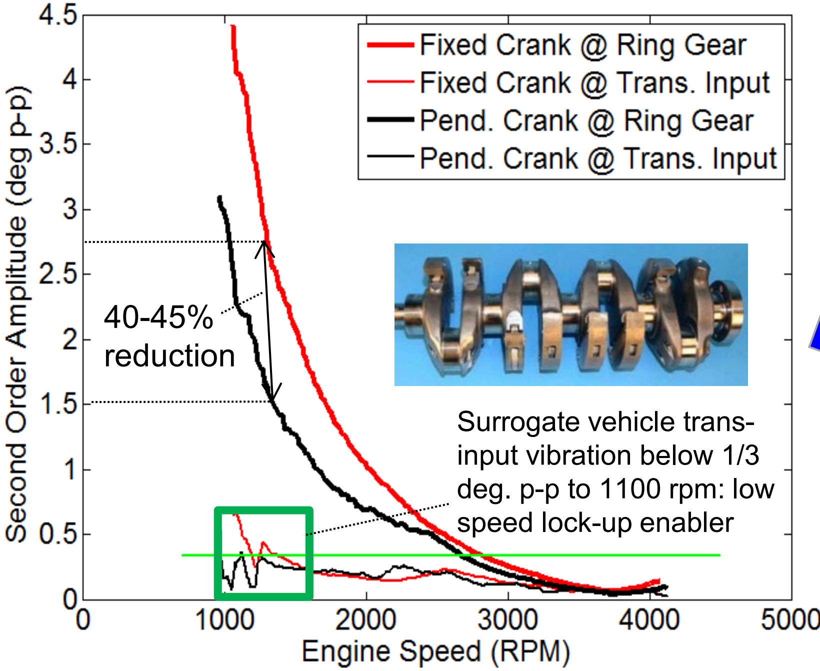
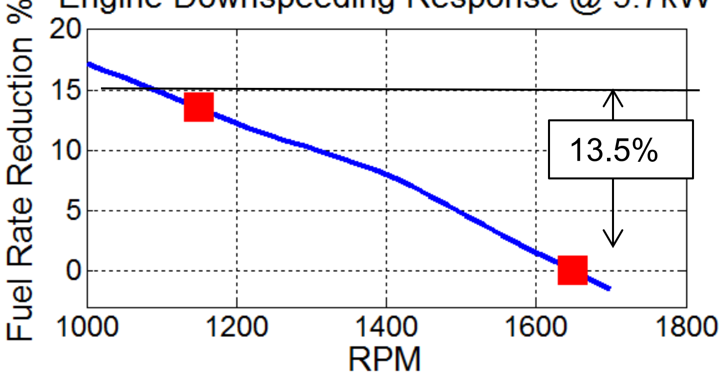
Ideal Engine Operation - Low Lock-up Speed

Engine Downspeeding Enabler

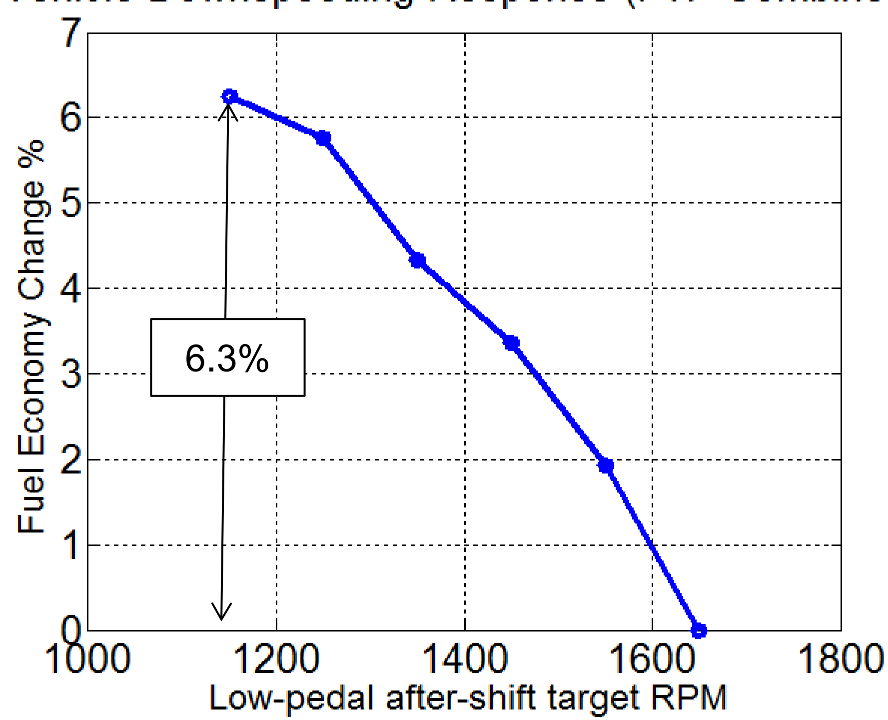


Engine Downspeeding Response @ 5.7kW



Assessed Fuel Economy Gain
Over Baseline = 6.3 % (combined)

Vehicle Downspeeding Response (FTP Combined)



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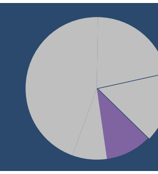
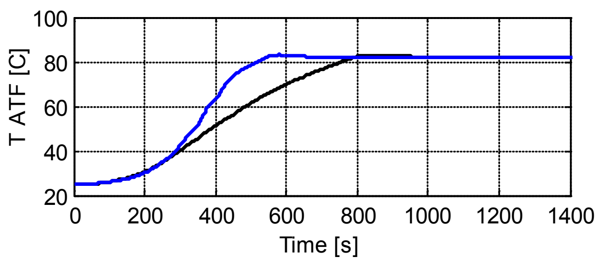
Thermal System Control



Rapid Warm-Up Time Optimization

OSU developed an optimized thermal system control strategy to transfer energy from engine coolant to oil and transmission fluid (ATF), achieving rapid warm-up

Increased temperatures reduce viscosity and friction losses, improving vehicle fuel economy



System achieves a 35% transmission fluid warm-up time reduction

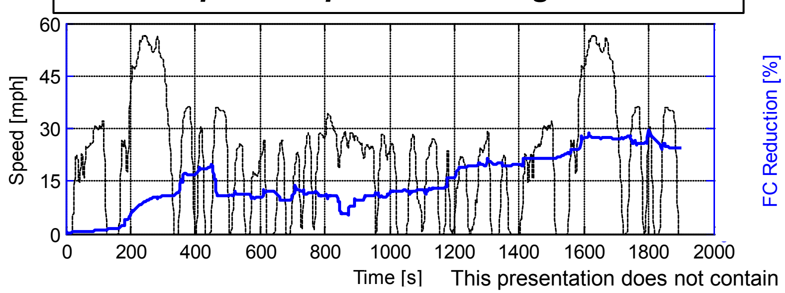
Energy-Efficient Coolant Temp Conditioning

Control algorithm coordinates hybrid coolant pump, electric thermostat and radiator fan to optimize energy consumption during fluid conditioning

An energy balance conducted in simulation illustrates the effects of the control strategy in reducing various energy losses on the engine crankshaft

Energy Loss	*Baseline*	*Optimized*	*Difference*	*% Reduction*
Transmission	*2.838 MJ*	*2.755 MJ*	*0.083 MJ*	*3.0%*
Engine	*0.716 MJ*	*0.679 MJ*	*0.037 MJ*	*5.2%*
Coolant Pump	*0.147 MJ*	*0.125 MJ*	*0.003 MJ*	*15.4%*
Radiator Fan	*0.032 MJ*	*0.007 MJ*	*0.025 MJ*	*78.9%*
Total	***3.733 MJ***	***3.566 MJ***	***0.168 MJ***	***4.5%***

Warm-Up & Temp Conditioning Combined

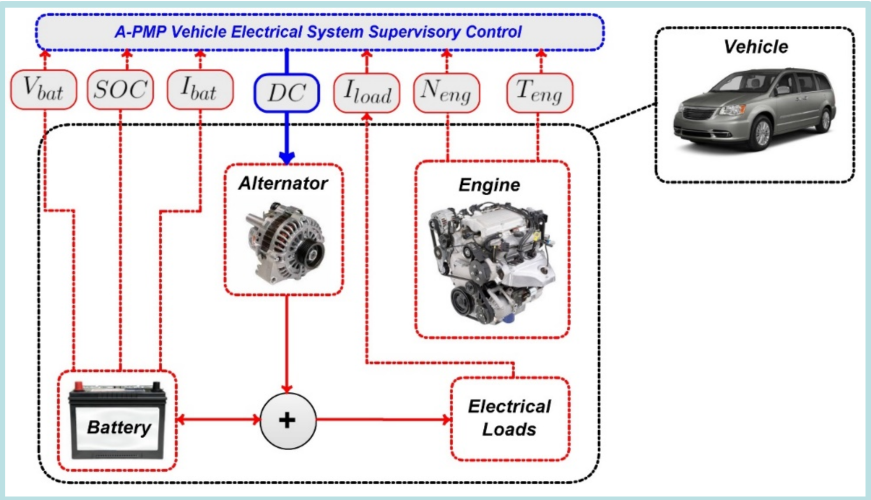


% Fuel Economy Improvement		
City	***Highway***	***Combined***
1.1%	***0.5%***	***0.85%***

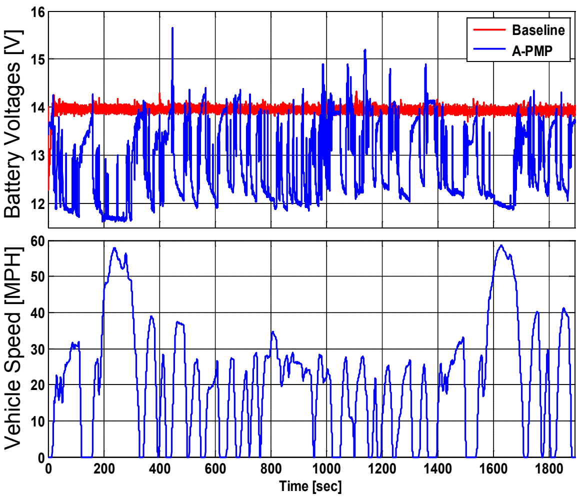
Ancillary Loads Reduction

Vehicle Electrical System Control

OSU developed a supervisory energy management strategy to utilize the battery as an energy buffer to reduce alternator loads, improving fuel economy

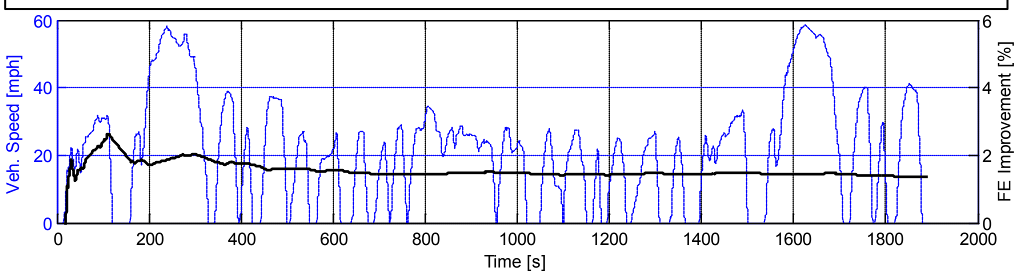


The OSU control (Adaptive Pontryagin Minimum Principle, A-PMP) manages the current split between battery and alternator for fuel economy, in presence of constraints (on voltage, current and battery charge)



Experimental tests conducted *in vehicle* show that the control strategy improves fuel economy and maintains battery charge without degrading its life

Fuel Consumption Comparison with Baseline Control Strategy



% Fuel Economy Improvement		
City	***Highway***	***Combined***
1.3%	***0.8%***	***1.0%***

Vehicle

Two vehicles were built for development and demonstration of performance, emissions and fuel economy

Accomplishments:

- Packaging: Emissions and fuel economy hardware was packaged in the vehicle including thermal protection
- Communication: Network utilizing a Gateway was developed to manage the communication between the vehicle and powertrain systems
- Software: Prototype control software was developed to manage the operation of emissions and fuel control devices
- Instrumentation: Full powertrain instrumentation was complete and packaged in vehicle Stow-n-Go compartment
- Thermal Management: High and Low Temperature Radiators were developed and packaged to efficiently manage thermal energy

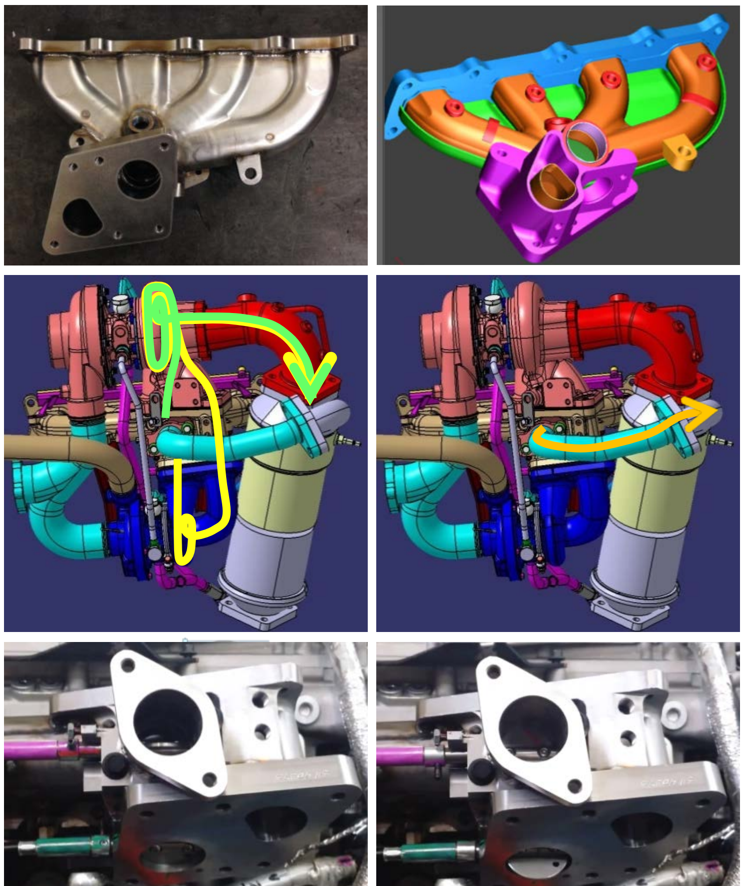
Vehicle #1

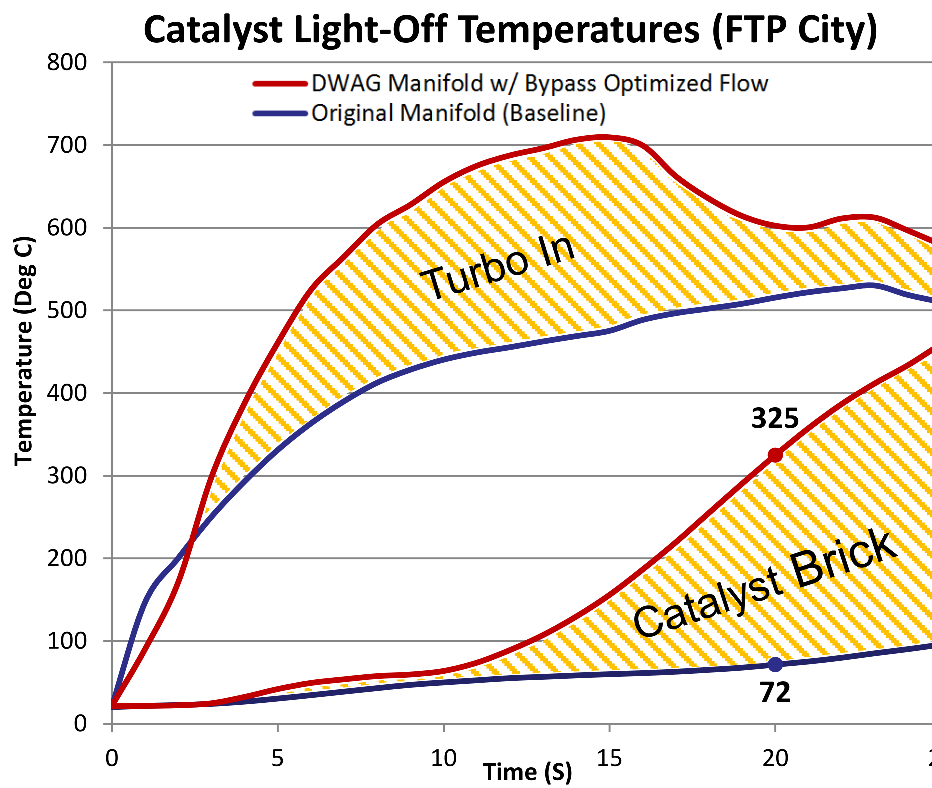
Vehicle #2

Instrumentation

Cold Start Emissions Control

- Low catalyst temperatures were observed during the FTP cycle (especially at cold start)
- Exhaust system mass was decreased with Dual Wall Air Gap (DWAG) exhaust manifold and optimized exhaust flow path

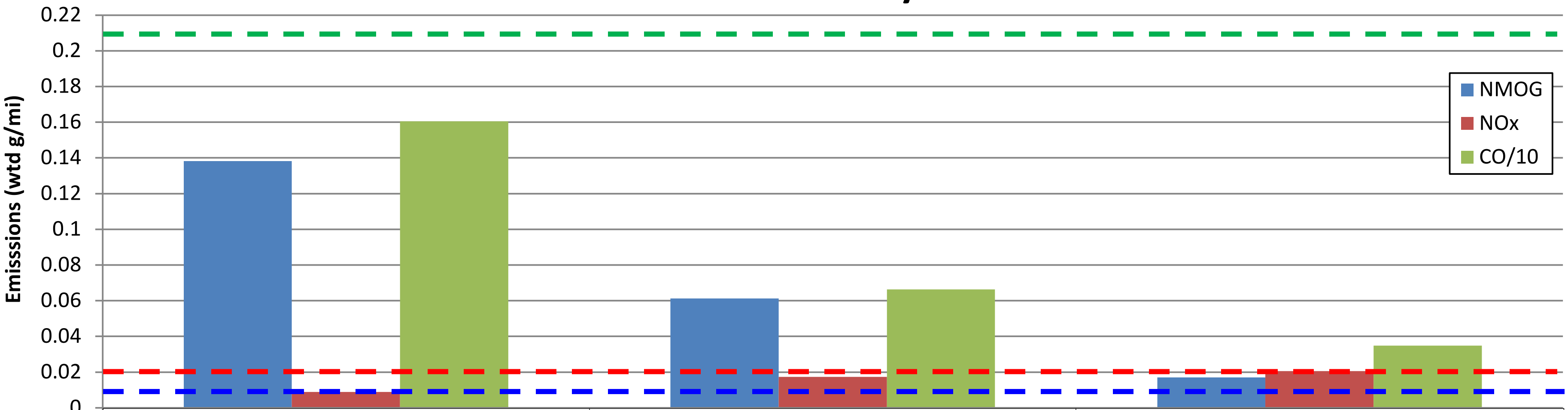


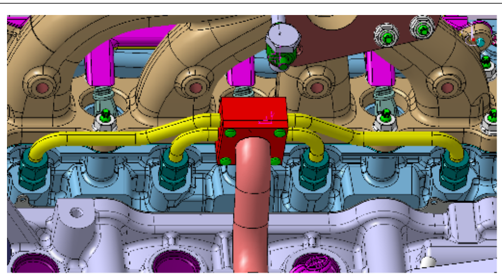


Hardware changes resulted in 250ºC catalyst brick temperature increase

Emissions Results (Hardware Evaluation)

Powertrain Test Cell FTP City Emissions Results



Secondary Air	Secondary Air	Secondary Air
Cast Stainless Steel Manifold	**DWAG Manifold**	DWAG Manifold
	Bypass Tube	Bypass Tube
	Flow Diverter Valves	Flow Diverter Valves
		Optimized Catalyst
		

ANL Dual Fuel: Gasoline + Diesel

CFD Modeling

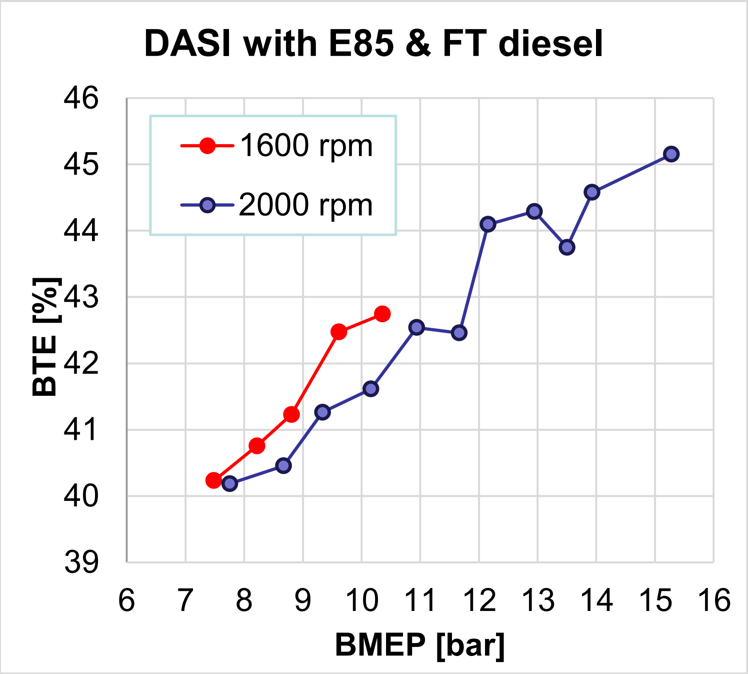
- Extensive validation of diesel & GDI single and multi-hole sprays against X-ray data from the Advanced Photon Source
- Both RANS and LES turbulence models tested - both captured trends well
- Genetic Algorithm used to optimize key engine parameters under Diesel Micro Pilot (DMP) operation

Engine Testing: Conventional Diesel and Gasoline Fuels

- Achieved 210 g/kW-hr BSFC during Diesel Assisted Spark Ignition (DASI) operation
- Decreased the diesel percentage needed for DASI operation by 3%

Engine Testing: Alternative Fuels (Fischer Tropsch Diesel and Ethanol Blends)

- Increased DASI operation Break Thermal Efficiency from 40% to 45% using E85 and FT diesel
- Knock does not limit efficiency like with conventional fuels
- Increased DMP operational range from 160 kPa boost down to 130
- Increased off-peak engine Break Thermal Efficiency by 2 – 3%
- Decreased the diesel percentage needed for DASI and DMP operation by 5%



Partnerships / Collaborations

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

BOSCH: 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

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

The Ohio State University: Developed Vehicle Energy Simulator (VES) and supervisory controller (Vehicle Energy Manager – VEM) that oversees and integrates energy management of vehicle subsystems

Project Summary

- A downsized, highly-diluted, spark-ignited concept engine has been demonstrated and comes very close to meeting all the project goals
- Fueling with two fuels, though very efficient, does present challenges
  - Durability / fouling of the fuel injector for the lesser-used fuel
  - A single, high performance fuel would be preferred
  - For the demonstration vehicle SI case, it means a higher Octane fuel
- High engine efficiency, presents challenges as well
  - Namely low exhaust temperatures and poor catalyst performance
  - Further exploration in developing catalyst materials that operate at lower temperatures is of high value
- Two-stage turbocharging presents challenges regarding cold start emissions
  - A systems approach that addresses thermal mass and engine efficiency must be taken

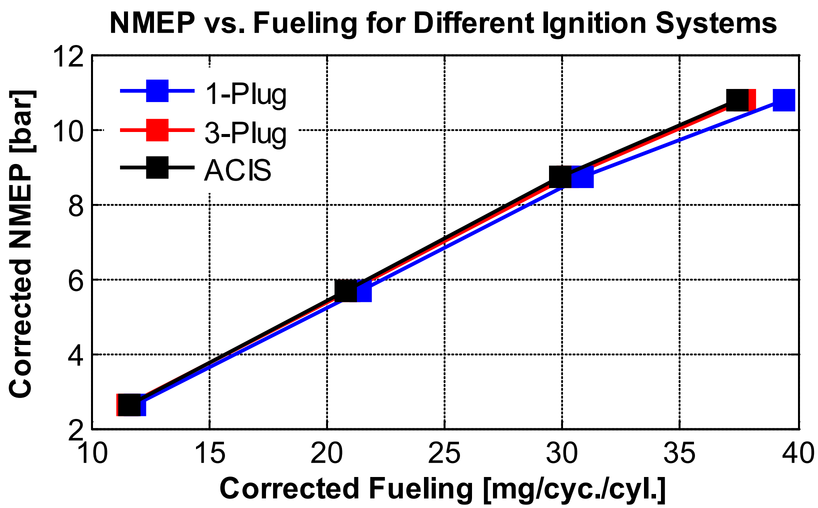
Thank You

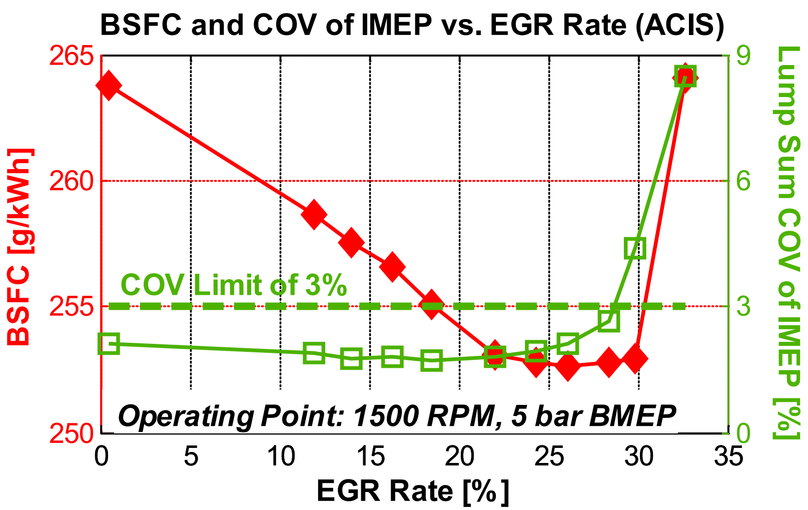
Technical Back-Up Slides

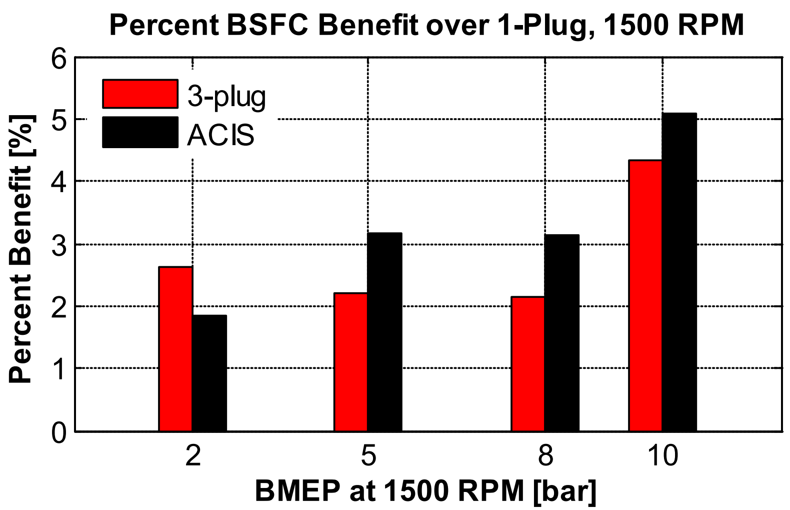
Ignition Systems Study

Results

- Systems tested: 1-plug and 3-plug baseline systems, Federal Mogul Advanced Corona Ignition System (ACIS)
- For each ignition system, EGR rate at each operating point is selected to minimize BSFC while maintaining combustion stability
- All systems tested thus far show 1-5% benefit over single-plug conventional system







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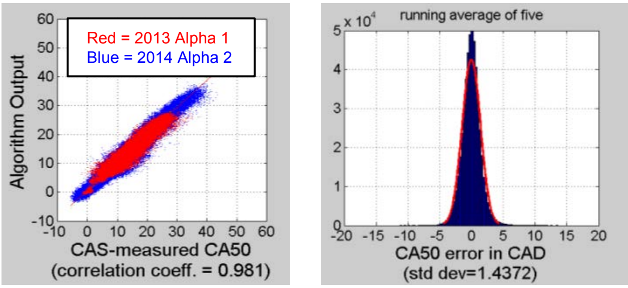
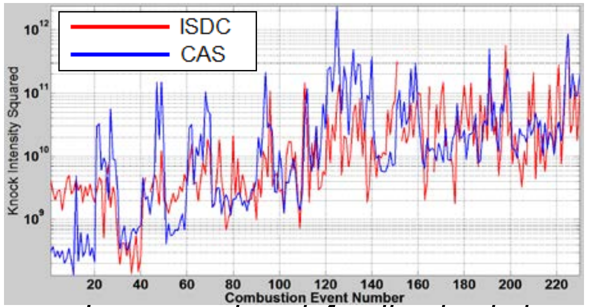
Ion Sense / Combustion Feedback

- Delphi Ion-Sense Combustion Sensing
  - Ignition Coil technology coupled to an Ion Sense Development Controller (ISDC). ISDC electronics have been updated to accept a wider range of ion current input that is generated by the Alpha 2 engine at high speeds and loads
- Algorithm and Software Development
  - All algorithm and software development activities have been completed for all combustion feedback parameters including combustion phasing, knock, and combustion stability
- Real-Time Ion-Sense Combustion Feedback on Dyno and Vehicle
  - Real-time combustion feedback has been implemented and demonstrated on three engine dyno installations and installed on two vehicles
- Combustion Phasing
  - Combustion phase detection range of operation expanded by 38% from last year's performance
- Knock Detection calibration work continues
  - Refinement for combustion feedback spark control

Ion-sense Combustion Feedback hardware integrated into demonstration vehicle for real-time control



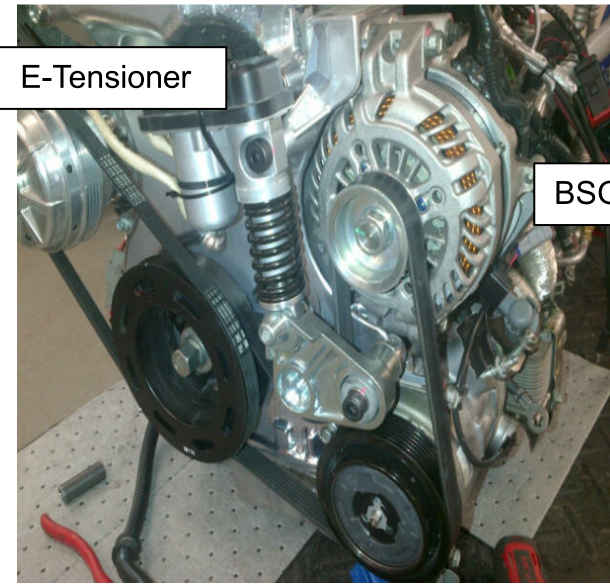
Combustion phasing range extended while maintaining accuracy



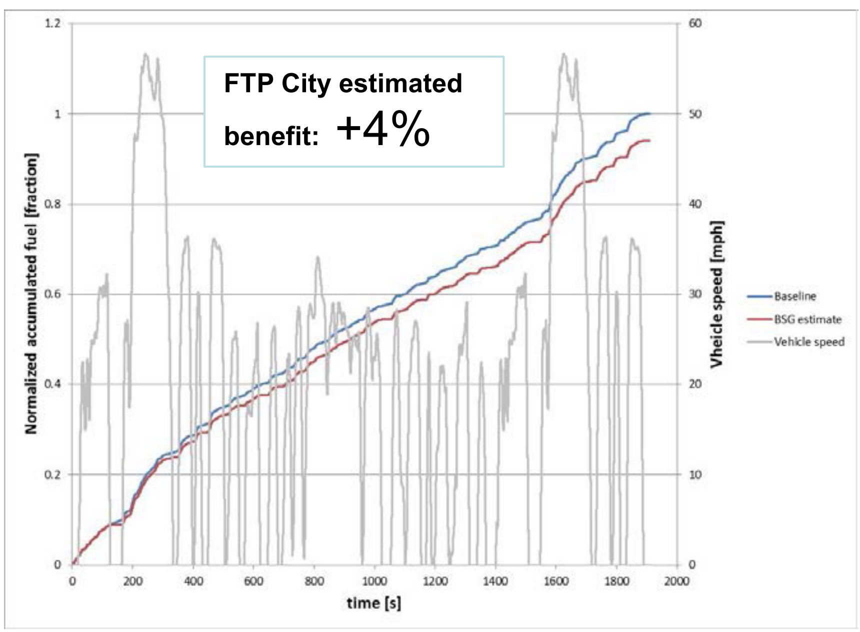
Ion-sense knock feedback mimics pressure-based reference

Vehicle Status - BSG

Belt-Starter Generator (BSG) was intended to be used for Stop / Start operation, but it is not likely needed to achieve the 25% fuel economy savings. If needed, the BSG reduces fuel consumption by shutting off the engine during idle conditions saving an estimated 4% fuel during an FTP city cycle (3.2% savings combined)



Stop Start FTP FE benefit estimate



Accomplishments:

- BSG is operational and able to maintain vehicle battery charge and hot start the vehicle
- Calibration complete on the E-Tensioner torque request vs. tensioner force
- Prototype software was developed to control transmission, E-Tensioner, and BSG during a shut down and start up event

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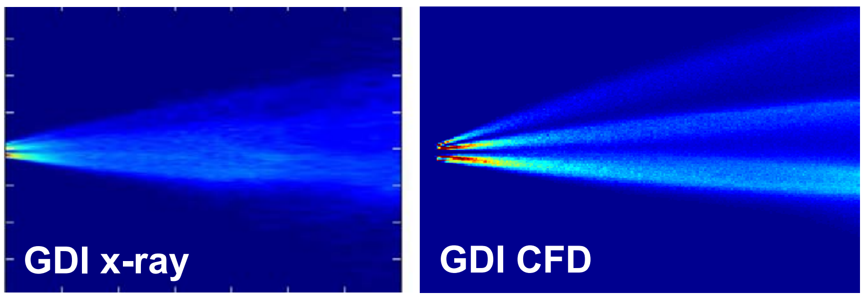
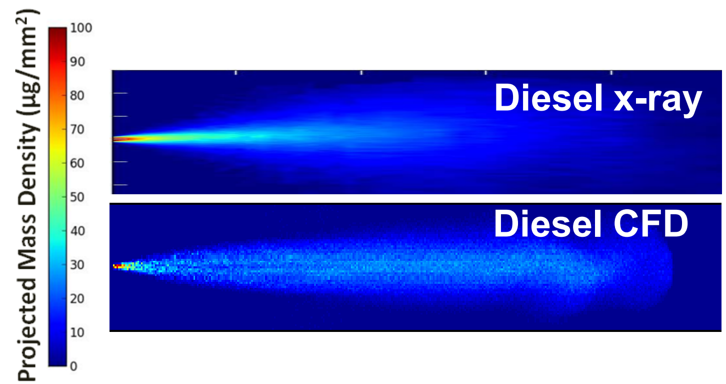
ANL Spray Modeling & Engine Optimization Through CFD

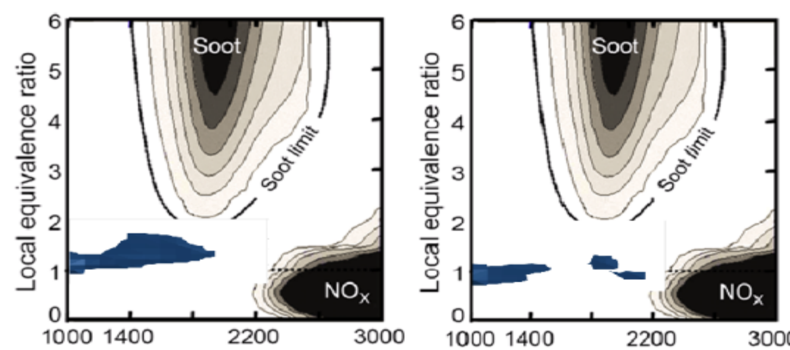
- Extensive validation of diesel/GDI single and multi-hole sprays against x-ray data from APS





- Both **RANS and LES turbulence models** tested. Both models **could capture global trends quite well**. The need for improved turbulent dispersion model with LES was identified
- **Genetic Algorithm** was used to **optimize the key engine parameters** under DMP stable conditions

Parameters	Baseline	Optimized
EGR ratio (%)	35.3	35
ICL (° CA ATDC)	461.8	452
DMP ratio (%)	13.4	6.6
DMP SOI (° CA BTDC)	19.5	27.8
Soot (g/Kw-h)	0.04	0.01
NO_X (g/Kw-h)	0.08	0.06



- DASI or other highly unstable operating conditions need advanced LES turbulence modeling to define a criteria for stability