MICHIGAN STATE UNIVERSITY

Argonne NATIONAL LABORATORY

Visteon

MAHLE Powertrain

DoE Optimally Controlled Flexible Fuel Powertrain System

Principal Investigator/Presenter: Paul Kilmurray

Organization: MAHLE Powertrain, LLC

Date: May 19th, 2009

Project ID # : ft_11_kilmurray

This presentation does not contain any proprietary or confidential information

Overview

MAHLE Powertrain

- **Timeline**

Phase 1	1/1/2007	- 6/30/2008
Phase 2	7/1/2008	- 6/30/2009
Phase 3	7/1/2009	- 5/20/2010
Phase 4	5/21/2010	- 12/31/2010

  Phase 2: 70% complete (as of 03/20/09)

- **Budget**

  Total Project Funding (all phases)
  - DOE $1,911,426
  - Recipient $2,235,193

  Funding received (by 3/20/09)
  - Phase 1 FY 08 $91,190
  - Phase 2 FY 09 $762,113

  $853,303

- **Barriers**
  - Target: Match Gasoline Performance with E85, minimize fuel consumption difference
  - Development of a cost effective and reliable full flex fuel engine and control system

- **Partners**
  - Michigan State University
George Zhu, Harold Schock
  - Visteon Corporation
David Hung
  - Argonne National Laboratory
Steve McConnell, Thomas Wallner, Robert Larsen
  - MAHLE Powertrain (project lead)
Simon Thwaite

Objectives

MAHLE Powertrain

- Develop, optimize and demonstrate using design analysis, computer modeling and a prototype engine, a pathway towards:
  - Flex Fuel Vehicles (FFV's) that show a minimized fuel economy penalty when operating on any blend level of ethanol up to E-85 as compared to a conventional gasoline fueled vehicle
  - FFV's that meet US Environmental Protection Agency (EPA) and State emissions regulations (Ultra Low Emissions Vehicle (ULEV))
- Demonstrate a new, commercially viable engine which is optimized for E85 operation, with seamless optimization for other blends:
  - Show minimum economy impact of running E85 when compared to gasoline
  - Show no degradation in vehicle emissions running E85 when compared to gasoline
  - Allow the engine to run at various levels of ethanol fuel content up to 85 percent
  - Demonstrate superior engine performance by fully exploiting the properties of E85
    - Performance increase is incentive for E85 use – displacing more gasoline
  - Help DoE promote the economy and social benefits, to the nation, of using E85 fuel

Objectives Over Past Year

MAHLE Powertrain

Phase 1 - Applied Research

- Review and confirm the high level design specifications for the proposed study engine
- Perform a detailed simulation and analysis for the proposed I3 study engine and a baseline 2.2l DI engine for both gasoline and ethanol blends. Using GT Power (engine) and ADVISOR (engine in vehicle) modeling provide comparisons of fuel economy and performance.
- Initial assessment of the hardware technical & economic viability
- Social Benefits Analyses – for fuel saving and emission reduction for US from 'oil well to pump' (vehicle engine)

Phase 2 - Exploratory Development

- Optical Engine Design & Fabrication
- In-Cylinder CFD Modeling (Injector Spray)
- Fuel injector design optimization
- Ionization based Ignition System design
- Update engine component design as required
- Procurement of test engine parts
- Closed Loop Combustion Control System
  - Mean Value Engine Model Development
  - Control System h/w & s/w Design
- Baseline comparator engine procurement and dynamometer testing on gasoline and ethanol blends

Milestones

- **BP 1: Milestone # 1 06/30/08**
  - Fundamental Engine Simulation Complete ✓
  - Social Benefit Analysis ✓
  - High Level Component Specifications ✓
  - Proof of Technical/Economic Viability ✓
- **BP 2: Milestone # 2 03/16/08**
  - MAHLE R3 Engine Design Update ✓
  - Major Components procured ✓
  - Design & Fabricate Single Cylinder Optical Engine **50%**
  - Fuel Injector Design **80%**
  - Ionization Ignition System Design **80%**
- **BP 2: Milestone # 3 06/15/09**
  - CLCC control system design **80%**
  - Base Comparator Engine Procurement & Instrumentation ✓
- **BP 3: Milestone # 4 12/31/09**
  - Single Cylinder Control System complete
- **BP 3: Milestone # 5 04/30/10**
  - Single cylinder engine testing complete
- **BP 3: Milestone # 6 05/20/10**
  - Multi cylinder E85 engine & control system assembled and broken-in
  - Baseline engine performance and emission tests and HDC analyses complete
- **BP 4: Milestone # 7 12/31/10**
  - Multi cylinder E85 engine tests complete
  - Efficiency/fuel economy data analyzed
  - Commercialization analysis
  - Final program report

Approach

MAHLE Powertrain

- Develop a flexible fuel powertrain that provides volumetric fuel economy, when operating on E85, similar to, or better than, a current gasoline powertrain of similar performance
- Use of existing technology, with suitable modifications, integration actions and tuning to realize a production and commercially viable solution
- Key enablers include
  - **Downsizing** : Aggressive reduction in swept volume combined with
    - Direct Injection
    - Turbocharging
  - **Increased Compression Ratio** : Takes advantage of ethanol's higher octane rating & increased heat of vaporization
  - **Variable Valve Control**, **Exhaust Gas Recirculation** : Allow optimization across speed/load map, minimize pumping losses & optimize the combustion process
  - **Closed Loop Combustion Control** : Enables fully flexible fuel operation
  - **Low Pressure Direct Injection** : Offers reduced parasitic losses

Approach
Based on existing MAHLE R3 design

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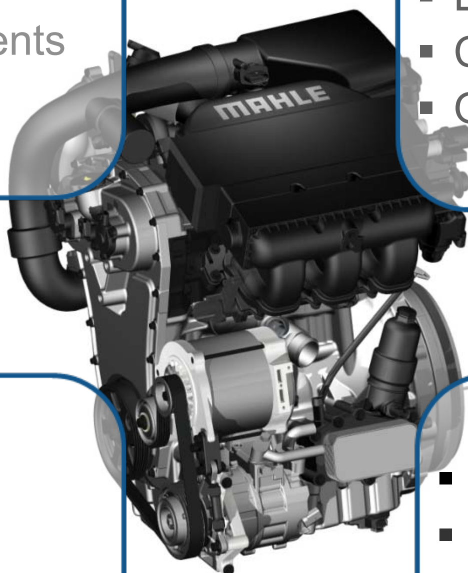
Simulation
- Combustion system (GT-Power)
- Vehicle effects (ADVISOR)
- Social benefit (GREET)
- High-level component requirements

Combustion System Design
- Injector analysis (CFD)
- Ignition system design
- Detailed 1D (GT-Power)
- Control system design (CLCC)
- Optical engine design



System Assembly/Baseline
- LPDI Injector build, Spray tests
- Ignition/Control system build
- E85 Optimized engine build
- Optical single cylinder tests
- Baseline engine tests (P & E)
- Highly diluted combustion study

System Development
- E85 Optimized engine tests:
- Cold start
- Performance & Emissions
- Results Analysis, model update
- Commercialization study

Baseline Engine Selection

MAHLE Powertrain

- A current US market 'state of the art' high volume engine was selected as a baseline comparator – GM 2.2L Ecotec DI
- Basic specifications:

	GM Ecotec Comparator	Initial Gasoline MAHLE R3	Proposed FFV MAHLE R3
Displacement	2198 cc	1200 cc	1200 cc
Cylinders	4	3	3
Bore / Stroke	86.0 mm / 94.6 mm	83.0 mm / 73.9 mm	83.0 mm / 73.9 mm
Fuel Injection	Direct	Direct	Direct
Aspiration	NA	Turbo	Turbo
Max Power	114kW @ 5600 RPM 155PS @ 5600 RPM	132kW @ 6000 RPM 180 PS @ 6000 RPM	132kW @ 6000 RPM 180 PS @ 6000 RPM
Specific Power	51.9 kW / Liter 70.5 PS / Liter	110.8 kW / Liter 150 PS / Liter	110.8 kW / Liter 150 PS / Liter
Max Torque	220 Nm @ 3800 RPM	286 Nm @ 3000 RPM	286 Nm @ 3000 RPM
Compression Ratio	12.0 : 1	9.25 : 1	TBC: 12.5 to 14.5

Engine Modeling

- GT Power models were constructed for GM & R3 engines
- Simulations run for E10 & E85, to determine fuel consumption over the engine speed / load range
- E22 & E50 results for MAHLE R3 estimated by linear interpolation
- Further R3 optimization runs performed
  - Compression ratio increased from 9:25:1 to 12.5 :1
  - E85 peak cylinder pressure limit of 140 bar maintained by retarding spark
  - Gasoline / E22 / E50 BMEP maintained through increased boost pressure
- Exhaust temperatures and peak cylinder pressure can be maintained within original R3 design limits
- Higher compression ratios may yield further fuel economy benefits

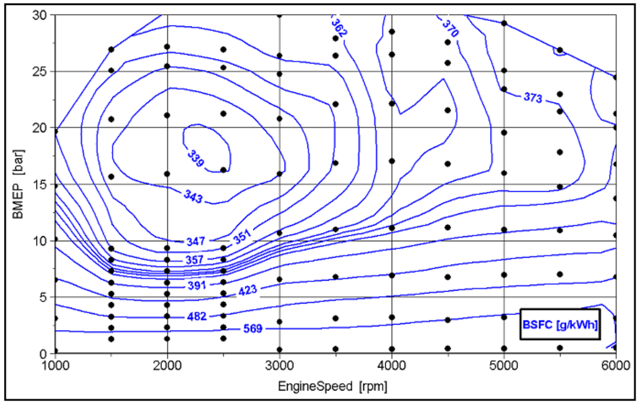


Figure 71. I3 E85 BSFC map with 12.5:1 compression ratio

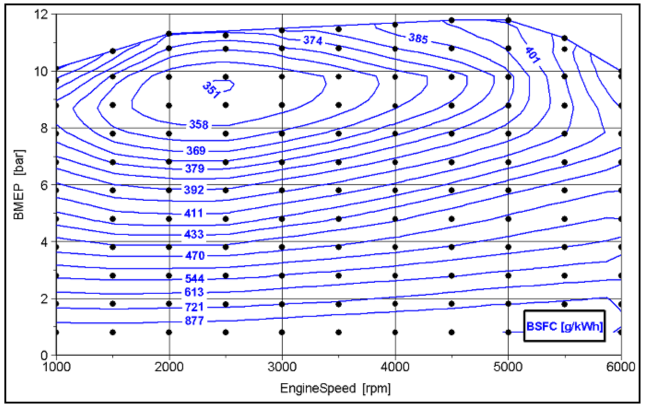
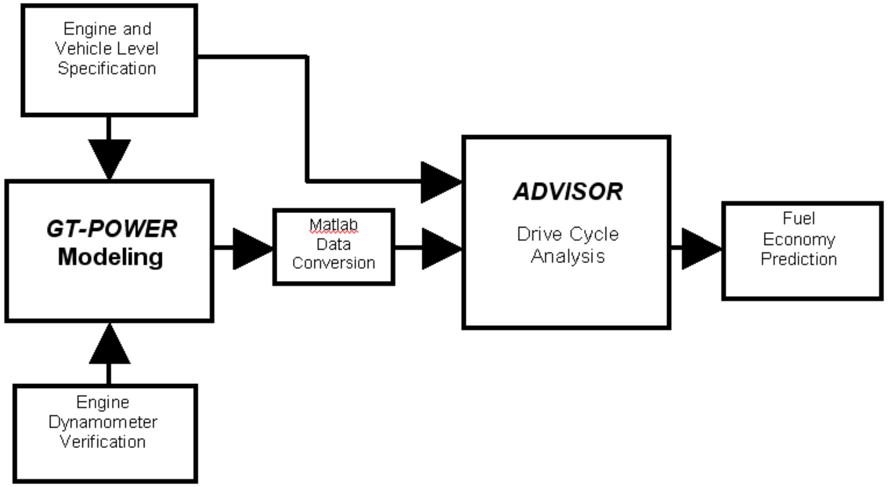
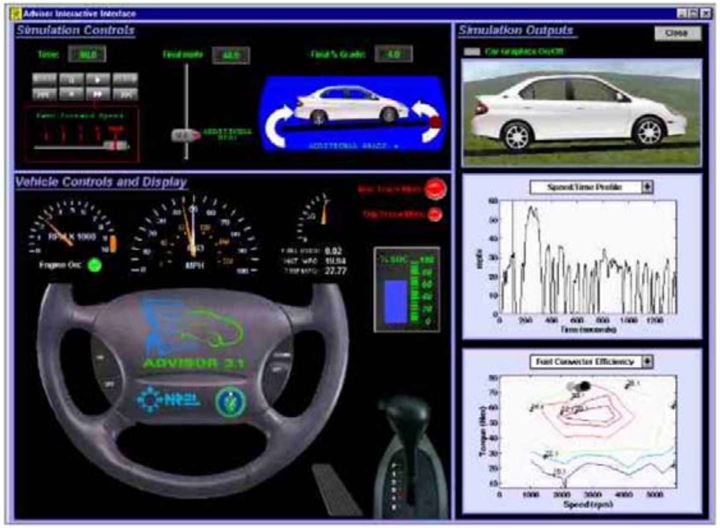


Figure 42. I4 Ecotec E85 BSFC map with 12:1 compression ratio

Technical Accomplishments/Progress/Results
Vehicle Performance/Economy Modeling

- Vehicle Models created in Visteon's ADVISOR software, based on GT Power engine model
- Model parameterized as Chevrolet Cobalt
- Transmission final drive ratio varied between Ecotec & R3 models
  - Reduced ratio for R3 takes advantage of increased torque to improve fuel economy
- Model runs simulated over FTP-75, HWFE & EUDC Drive Cycles
- Initially run with E85 & gasoline, subsequently corrected for E10
- Results indicate fuel economy penalty of E85 (Vs gasoline) reduced from 30% (typical) to 9%
- E85 FE improvement achieved with 20% performance improvement (0 – 60 mph)





Vehicle Performance/Economy Modeling

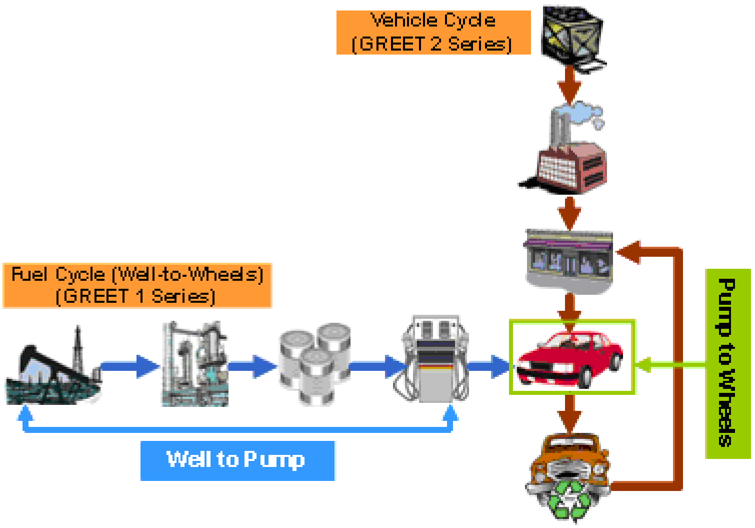
- Further E85 FE optimization possible by :
  - Compression Ratio >12.5:1
  - Further vehicle final drive ratio reduction
  - R3 friction reduction
    - Improved piston & ring pack
    - Split cooling system
    - 2 stage or variable oil pump
    - Cam profile, valve spring force
    - Rolling element camshaft bearings

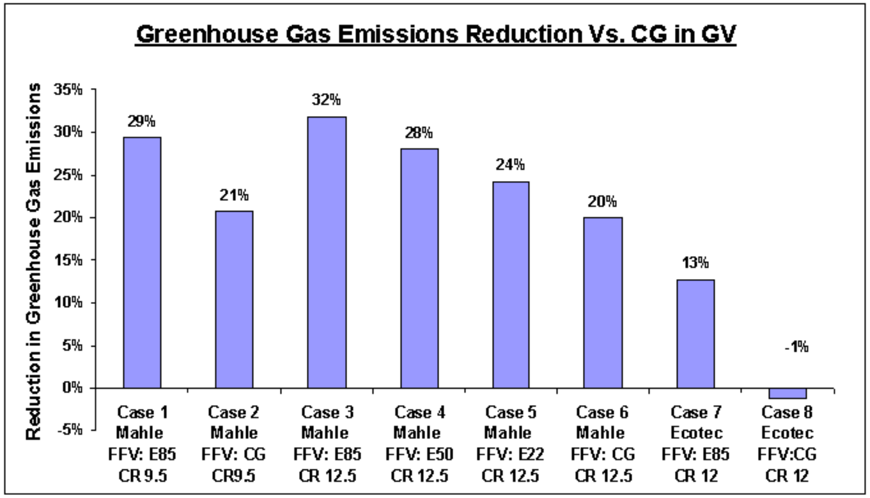
	Engine		FUEL	Ethanol Content	MPG				OVERALL EFFICIENCY (%)			0-60mph
	# Cyl	CR		%	FTP	HWFET	Combined FTP & HWFET	EUDC	FTP	HWFET	EUDC	Sec
Mahle with FD = 3.25	I3	9.25	E85	85%	23.4	29.9	25.9	26.0	9.5	18.2	15.8	6.8
			Gas	0%	35.5	45.6	39.4	40.1	9.8	19.0	16.6	6.9
	I3	12.50	E85	85%	26.9	34.9	30.0	29.9	10.9	21.2	18.1	6.6
			E50	50%	30.0	37.9	33.1	33.3	10.3	19.4	17.0	6.7
			E22	22%	34.1	43.4	37.7	38.2	10.2	19.4	17.1	6.7
			Gas	0%	37.4	47.8	41.5	42.0	10.4	19.8	17.4	6.7
Ecotec with FD=3.94	I4	12.00	E85	85%	20.9	25.7	22.8	22.5	8.5	15.6	13.6	8.3
			Gas	0%	31.4	38.6	34.3	33.8	8.7	16.0	14.0	8.3

	Engine		FUEL	Ethanol Content	MPG				0-60mph
	# Cyl	CR		%	FTP	HWFET	Combined FTP & HWFET	EUDC	Sec
MAHLE FD = 3.25	I3	12.50	E85	85%	26.9	34.9	30.0	29.9	6.6
Ecotec FD=3.94	I4	12.00	E10	10%	30.3	37.2	33.1	32.6	8.3
			% Difference		-11.2	-6.3	-9.3	-8.3	20.5

Social Benefits Analyses

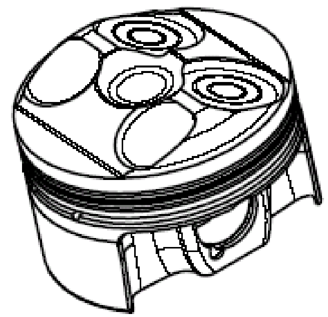
- GT Power modeling results were analyzed with GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) software
- This is a 'Wells To Wheels' analysis, calculating
  - Emissions of six criteria pollutants: VOCs, CO, NO_x, PM10, PM2.5, SO_x
  - Emissions of CO2-equivalent GHGs
  - Consumption of total energy
- Results indicate that optimized E85 R3 will reduce drive cycle GHGs by 33%, compared to Gasoline Ecotec baseline
- This substantial Green House Gas reduction is achieved with a significant increase in vehicle performance

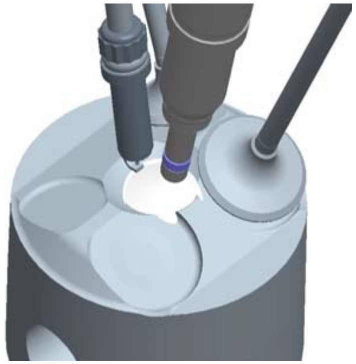


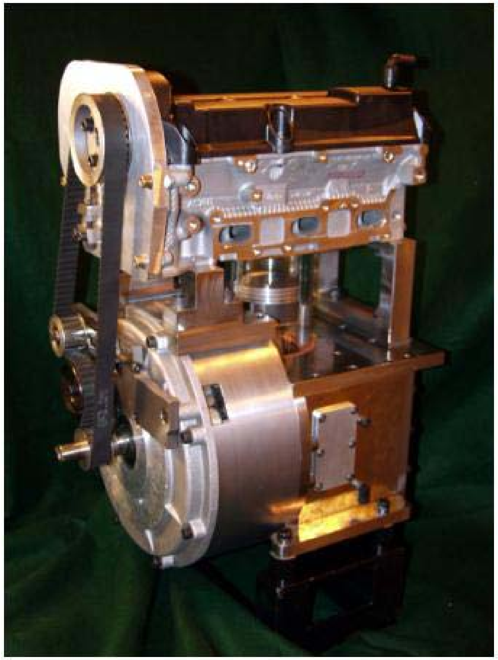


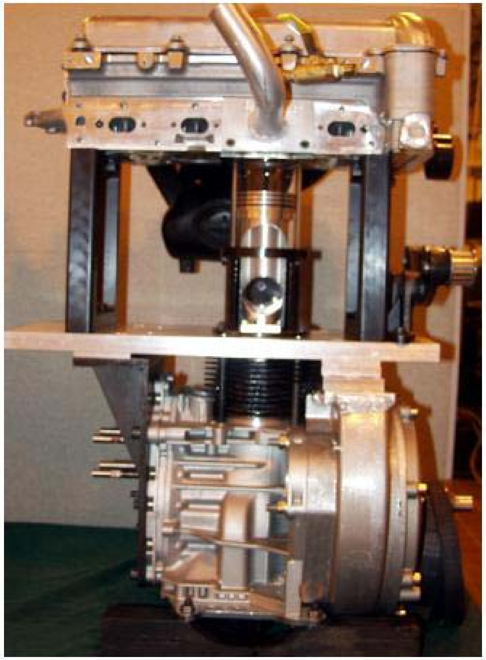
Optical Engine

- Design complete
  - Con rod designed & manufactured
  - Cylinder head components procured
  - Design of optical window & liner complete
- Physical testing planned with target compression ratio 13.5:1 (as indicated by GT Power simulations)
  - Motored flow visualization using laser & optical diagnostics for optimal mixture preparation
  - Firing tests to study combustion characteristics
  - Correlate in-cylinder pressure and ionization signals





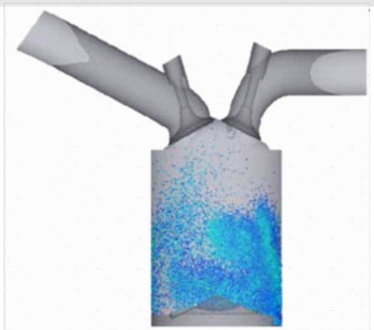




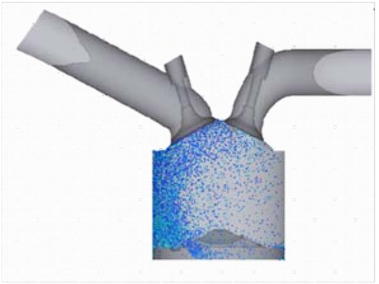
Technical Accomplishments/Progress/Results

In-Cylinder Mixture & Combustion Modeling

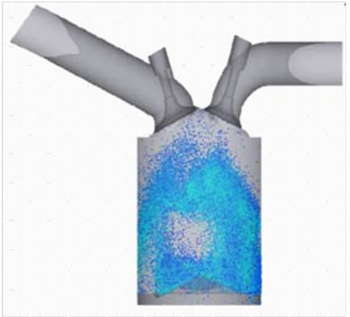
- Injector Design / Selection
  - Lower energy density of E85 demands selection of higher flow injectors
  - GT-Fuel Injector flow dynamics model complete
- In-Cylinder CFD Modeling with Convergent Science Inc.'s CONVERGE
  - 6- & 8-hole injector, gasoline & ethanol A/F distribution simulations complete
  - Combustion flame front simulations on-going
  - Results of further simulations will drive fuel injector selection & nozzle design



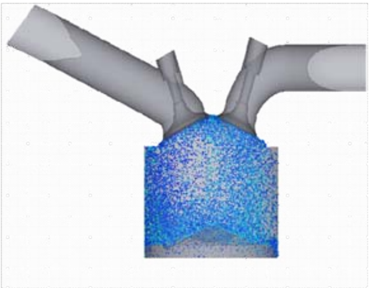
Ethanol, 6-hole, 180º BTDC



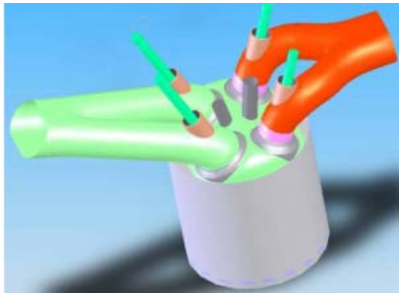
Ethanol, 6-hole, 90º BTDC

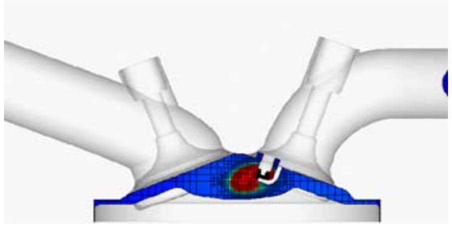


Ethanol, 8-hole, 180º BTDC

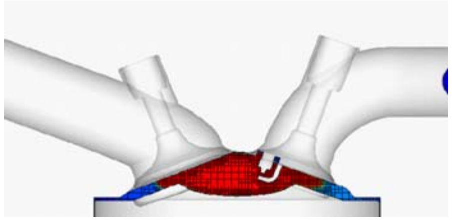


Ethanol, 8-hole, 90º BTDC





Combustion: 6º BTDC



Combustion: 0º BTDC

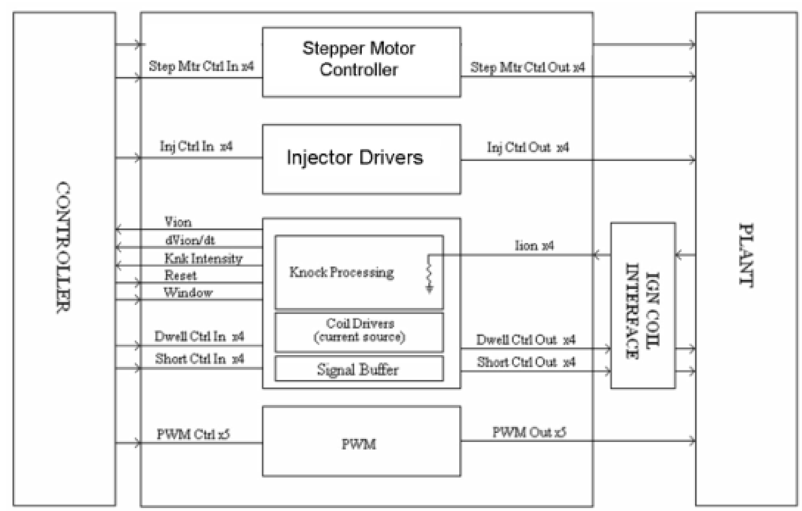
Technical Accomplishments/Progress/Results

Ionization Based Ignition System Design

- R3 features of high compression ratio, turbocharging and direct injection result in relatively high in-cylinder pressures
- These conditions demand high spark ignition energy & voltage to ensure adequate combustion stability
- Two current production DI coils, plus a high energy prototype ionization coil, are under consideration
- Ionization signals will be utilized for closed loop combustion control, knock detection, combustion stability control & inferred flex-fuel blend
- Ignition Interface Circuit to drive coils & provide ionization signal has been designed

Model-Based Control System Development

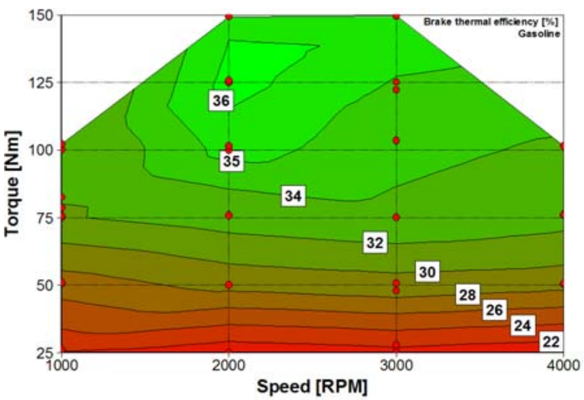
- Mean Value Engine Model Development
  - GT-Power engine model developed to generate calibration for MV engine model
  - dSpace Hardware-In-the-Loop simulator to be used for controller development
- Prototype Control System
  - Engine controller selected: Opal-RT
  - Engine Controller I/O Box designed

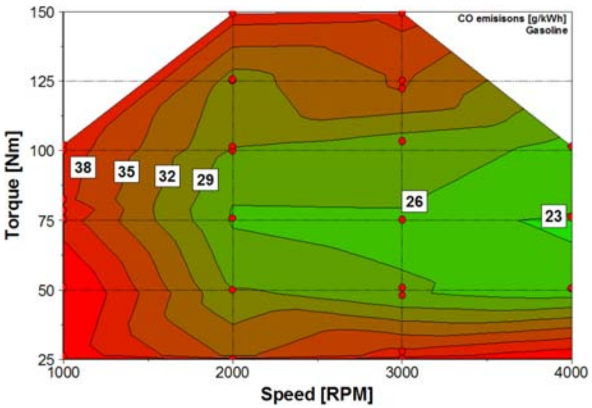


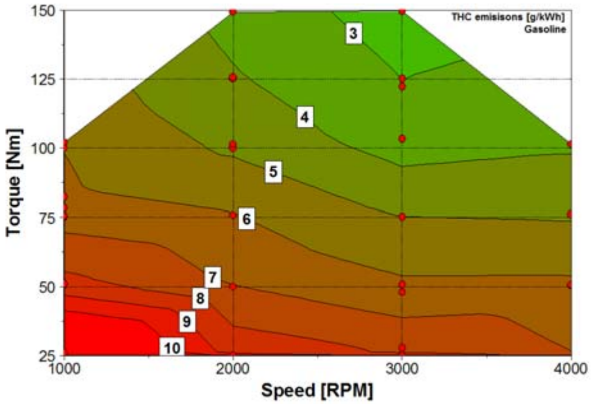
Technical Accomplishments/Progress/Results

Baseline Engine Benchmarking

- GM 2.2L DI NA Ecotec engine procured
- Dyno suitable Engine Controller obtained
- Ion sensing coil added to stock ignition system
- Baseline gasoline performance, fuel efficiency & emissions mapping complete
- Ion sensing tests conducted with gasoline & E85
- Next step includes baseline mapping with ethanol blends

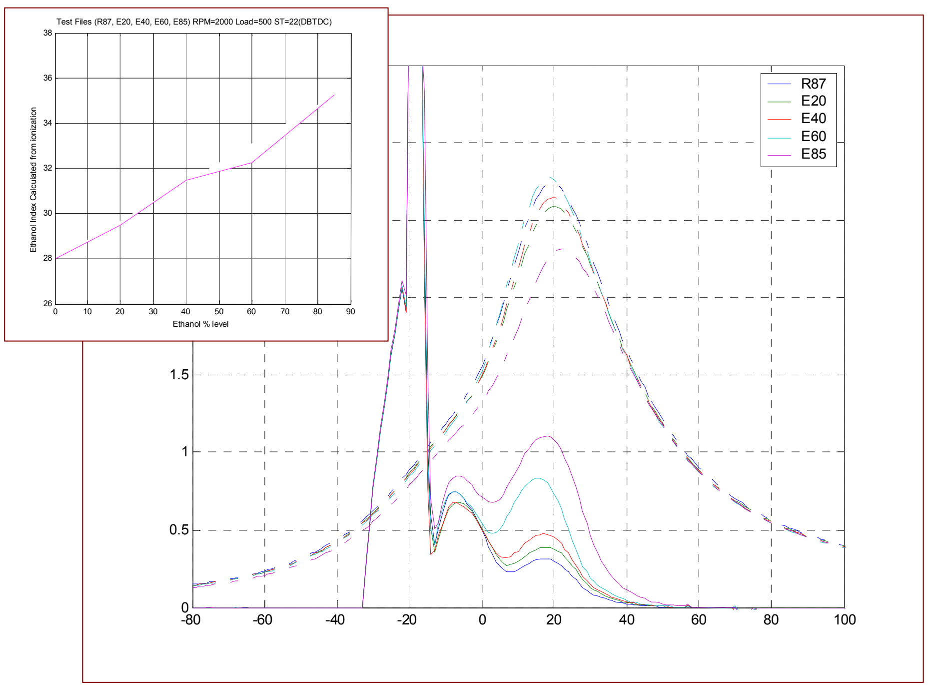




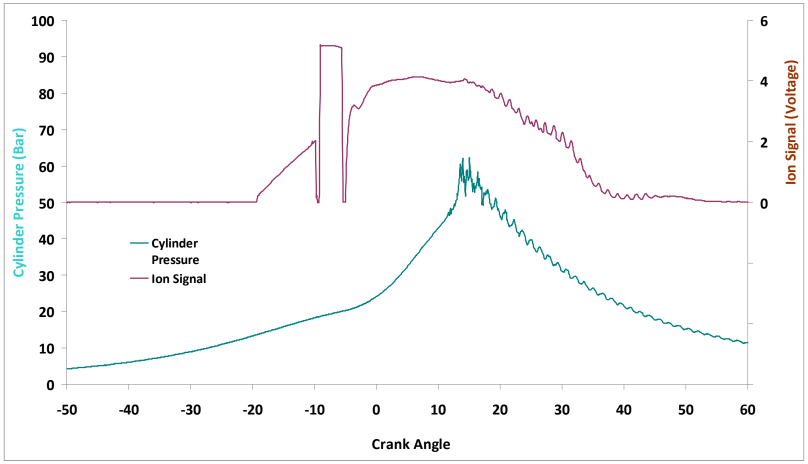


Ignition System with Combustion Feedback

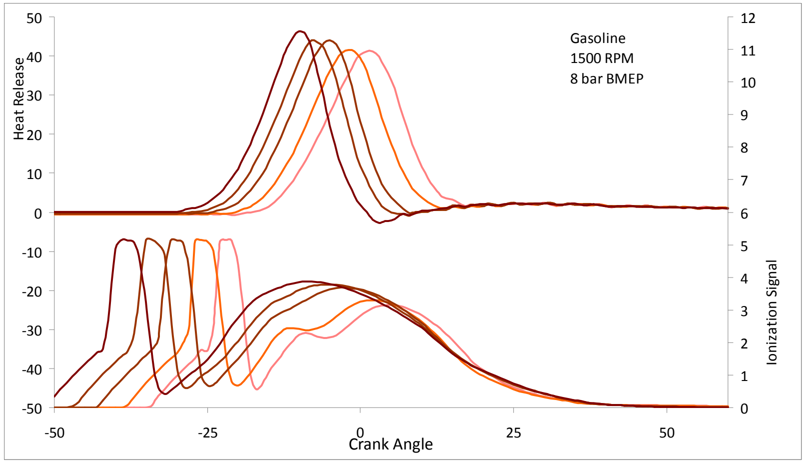
- Ionization signal is used to:
  - Infer fuel blend (% ethanol)
  - Determine combustion events and phasing
  - Knock detection



Fuel Blend Inference



Knock Detection



Spark Sweep to Show Combustion Phasing

Future Work (FY 2009 & FY 2010)

- Finalize injector design / selection
  - Fabrication of Injectors
  - Injector spray characterization
- Evaluate performance of single cylinder optical engine with blends of E85 and gasoline
  - Cold flow injection tests with varying boost and injection timing
  - Combustion tests with varying injection timing, boost pressure, ignition energy and timing
- Evaluate performance of single cylinder metal engine
  - Fuel economy and emission tests for blends of E85 and gasoline
  - E85 Tests Including cold start
- Assemble optimized MAHLE R3 engine
  - Assemble control system
  - Complete break-in dyno tests
- Test optimized R3 engine
  - Performance & emissions tests for E10, E85 and ethanol blends
  - Cold start capability tests
  - Estimate drive cycle fuel economy, based on dyno tests
- Results Analysis & Reporting
  - Report engine efficiency & FE results, compared to targets
  - Analysis of commercial feasibility of final design

Summary

MAHLE Powertrain

Relevance: Improvements in Ethanol blend flex fuel engine technologies are being developed to provide similar volumetric fuel economy to current gasoline powertrains of similar performance

Approach: Downsizing with use of existing technology, suitably modified, for a production and commercially viable solution

Key Enablers: Direct Fuel Injection, turbocharging, Increased compression ratio, Closed Loop Combustion Control, Variable Valve Timing

Technical Accomplishments:

- Engine modeled and vehicle simulations completed with gasoline & E85. Current improvement to existing ethanol efficiencies, (10% lower FE than gasoline) - further improvement expected
- GHG reduction of 33% predicted, compared to equivalent gasoline engine
- Single cylinder test engine designed and under construction for combustion analysis
- CFD model for injector spray characteristics and combustion
- Initial hardware designed and ordered for DI, ignition & CLCC systems
- Modeling adherence to 140 bar cylinder pressure limit and low exhaust temperatures for fuel blends indicate that an optimized E85 R3 engine is viable
- No economic concerns, as E85 optimized R3 is based on conventional, well established components and sub-systems
- CLCC yet to be commercially proven, but it is a fully developed and demonstrated technology

Collaboration: Mahle Powertrain (project lead), cosponsors: Michigan State University, Argonne National Laboratory, Visteon Corp.