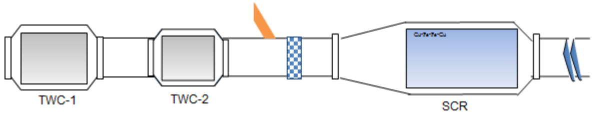
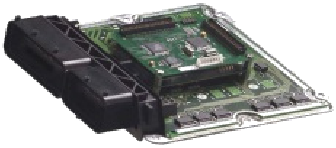
Lean Gasoline System Development for Fuel Efficient Small Car

Stuart R. Smith - Principal Investigator

GM Powertrain

May 17, 2013





2013 DOE Vehicle Technologies Program Annual Merit Review

Washington, DC

Project ID: ACE063

Lean Gasoline System Development

Overview

TIMELINE

- Project start: May 2010
- Project end: Sept 2013
- Project duration: 3 yrs 3m
- Percent complete: 90%

BARRIERS

- Engine efficiency improvement >25%
- Engine controls to meet regulatory and consumer requirements
- Emission control hardware cost competitiveness

BUDGET

- Total funding: $15,411,724
  - DOE share: $7,705,862
  - GM share: $7,705,862
  - DOE Funding FY12 $3,014,435
  - DOE Funding FY13 $276,308

PARTNERS

- RICARDO
- BOSCH
- umicore

Lean Gasoline System Development
Relevance – Program Objective

25% fuel economy improvement while meeting T2B2 emissions

- ✓ **Lean Combustion** - Generate fundamental lean gasoline combustion comprehension and design guidelines that would support implementation across multiple engine families
- ✓ **Lean Aftertreatment** - Optimize a lean aftertreatment system that combines passive NH3 generation with active urea dosing for minimized urea consumption under lean operating conditions
- ✓ **Lean Controls** - Develop engine and passive and active aftertreatment controls that work within production controls constraints to ensure compatibility with future ECU architectures

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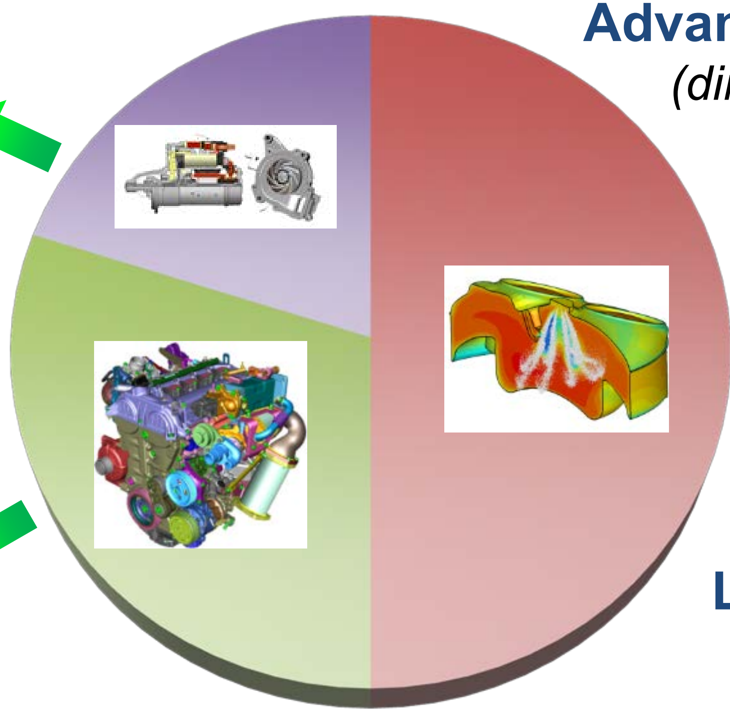
Approach / Strategy – Targeted Efficiency Improvement

Vehicle Integration
(12V stop/start, active thermal management)

Projection 5%

Advanced Dilute Combustion
(direct injection, cool EGR)



Projection 12.5%

Lean Dilute Combustion
(closely-spaced multiple pulse injection)

Projection 7.5%

Downsizing
(2.4L PFI to 1.4L DI Turbo)

* Projections formulated from dynamometer and SG5 vehicle data

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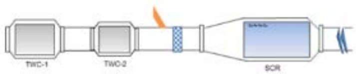
Approach / Strategy – Technology Development Plan

May 2012 | Nov 2012 | May 2013 | Aug 2013

Phase 2 Refinement

- **Downsize Boost Simulation**
- **Gen 2/3 Passive SCR Development**
- **Active SCR Development**
- **2.2L SG5 NA Vehicle Integration & Calibration**



Phase 3 Optimization

- **1.4L Lean Downsize Boost Design & Build**
- **Lean Boost Controls**
- **1.4L LDB Calibration**
- **Passive/Active SCR**
- **S/S & ATM Integration**
- **FE Optimization**
- **Demo**

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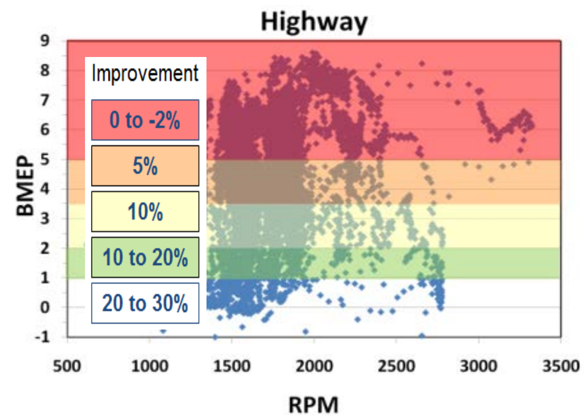
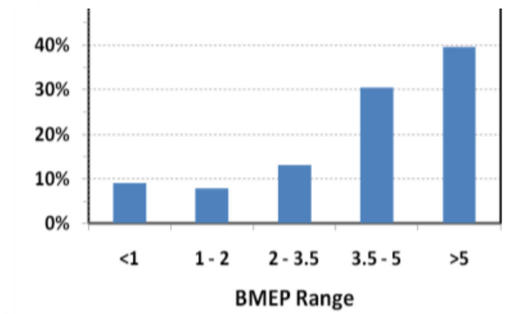
Accomplishments – Phase 2: SG5 NA Systems Refinement

SG5 Fuel Economy Limitations

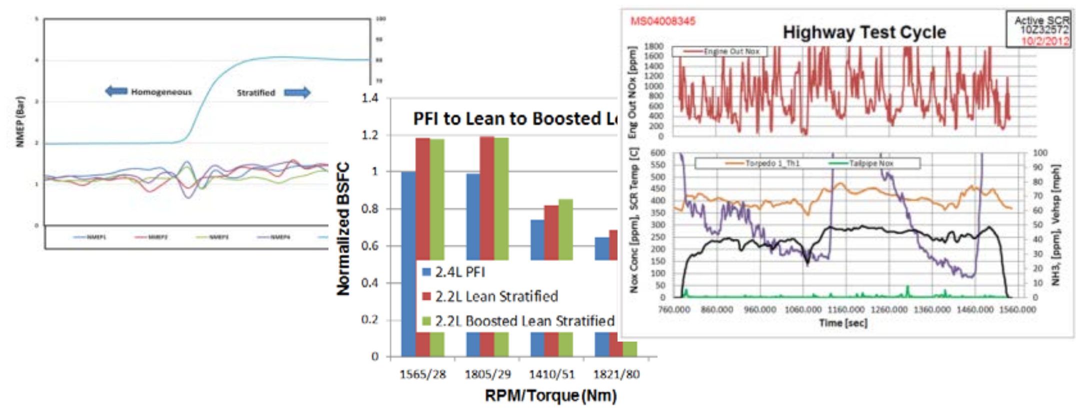
- ✓ Lean operation shows significant fuel economy improvement at light to medium loads
- ✓ Needed to extend the lean operating range to higher loads





SG5 Systems Refinement

- ✓ Enabled development of controls around lean-stoich transitions
- ✓ Enabled exploratory boost performance investigations
- ✓ Enabled refinement of multiple aftertreatment systems



➔ The SG5 NA engine would not meet FE targets. However, it enabled development of combustion system, lean aftertreatment (hardware and controls), and in-vehicle engine controls and calibration

GM Powertrain
Advanced Engineering

DESIGN BUILD SELL
THE WORLD'S BEST VEHICLES

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Accomplishments – Phase 2: SG5 NA Fuel Economy Improvement

Fuel Economy Simulation

- ✓ BSFC data for high usage speed / load points from FTP tests used to project fuel economy improvements
- ✓ Data does not include 12V Stop/Start and Active Thermal Management which is projected to provide additional 4-6 % combined fuel economy benefit

		Speed (RPM)	Load (n-m)	BSFC Improvement PFI to Lean NA
Urban	Idle	700	19	0%
	Zone 2	1335	27	17%
	Zone 3	1565	28	19%
	Zone 4	1805	29	18%
	Zone 5	1530	95	-1%
	Zone 6	1821	80	3%
	Zone 7	2250	101	0%
Highway	Zone 8	1410	51	18%
	Zone 9	1669	60	9%
	Zone 10	1461	114	0%
	Zone 11	1692	100	0%

	Projected FE Improvement	Measured FE Improvement
City	12%	12%
Hiway	8%	7%
Combined	10%	10%

➔ Good correlation between fuel economy projections and measured vehicle data

➔ SG5 NA Engine does not meet FE target

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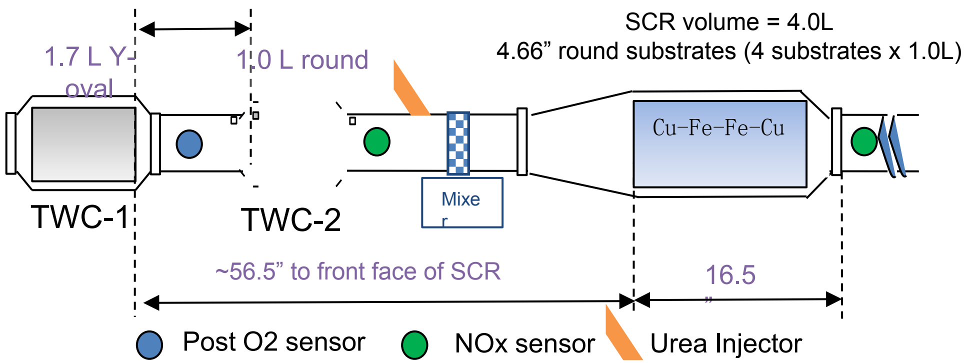
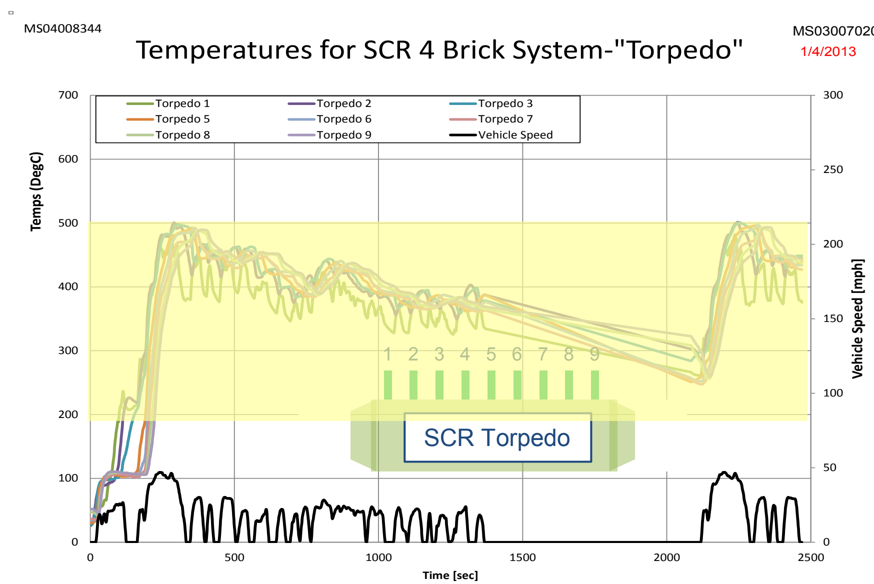
Accomplishments – Phase 2: Passive/Active Ammonia SCR System

Passive/Active Ammonia SCR System (PAASS)

- ✓ A portion of the NH3 is generated across three way catalyst with the remainder injected
- ✓ The selected TWC volume and formulation optimize the NH3 generation during lean-to-stoichiometric transitions





➔ The passive and active ammonia systems are combined to achieve the optimal aftertreatment to support lean and stoichiometric operation under all conditions

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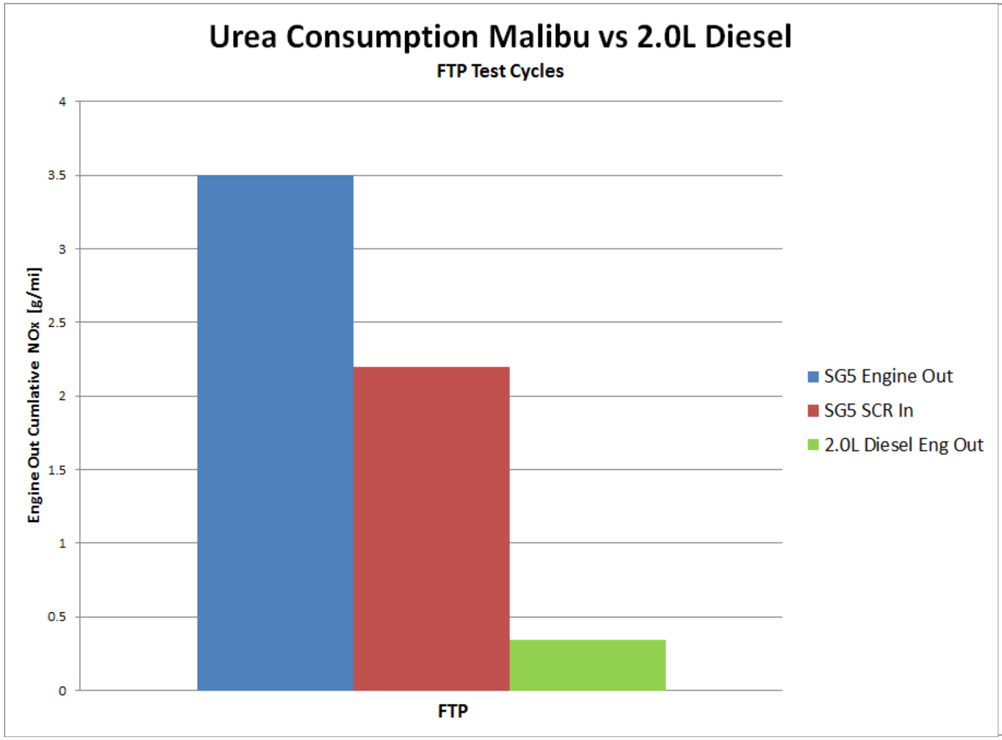
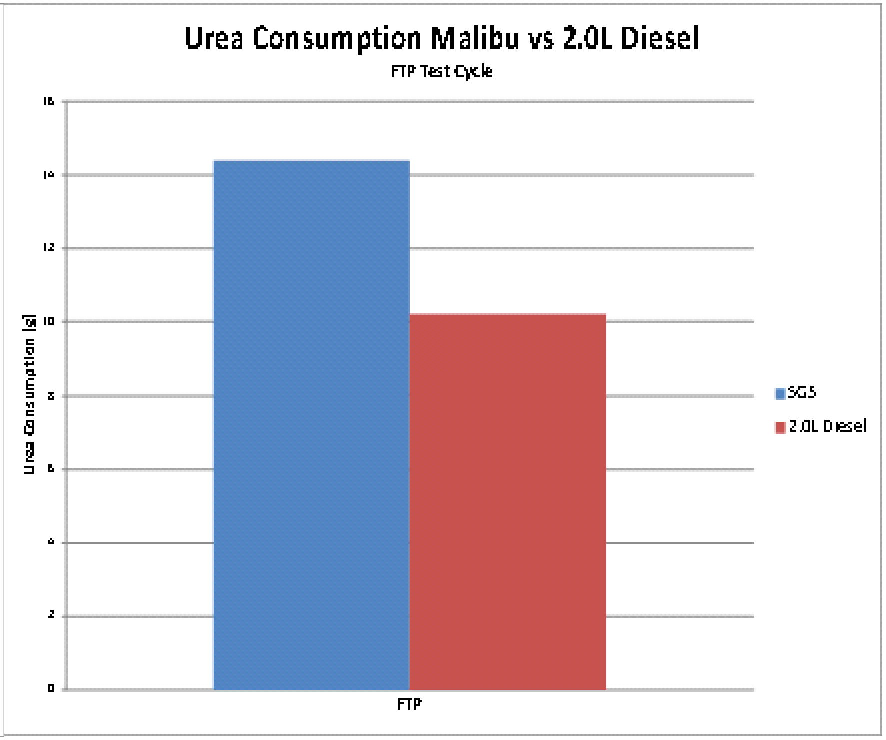
Accomplishments – Phase 2: Comparison with Diesel Vehicle





*Diesel information is from T2B5 package

Aftertreatment

- ➔ In order to achieve FE targets, engine-out NOx increases and the active urea system is incorporated to supplement the passive system
- ➔ Urea consumption is not linear with engine-out NOx due to passive NH3 generation and TWC reduction

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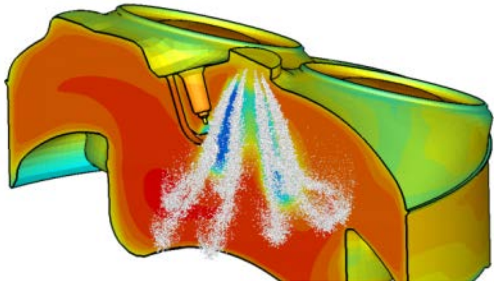
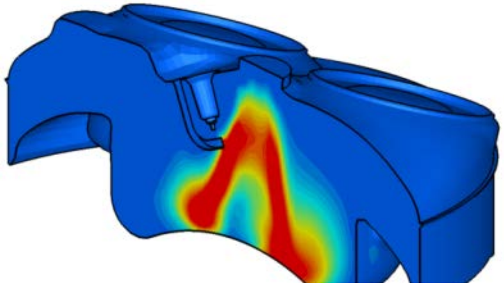
Accomplishments – Phase 3: 1.4L LDB Combustion Optimization

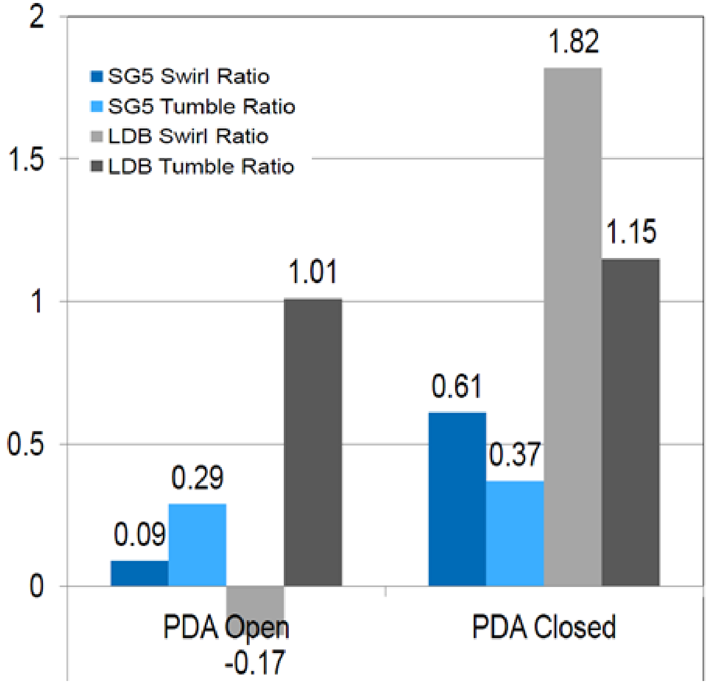


Fuel Spray Analysis



In-cylinder Fuel Equivalence Ratio Distribution Analysis

Swirl & Tumble Flow Bench



- ➔ Transfer the desired combustion characteristics of the SG5 to the new LDB engine
- ➔ CFD analysis to simulate the spray pattern and in-cylinder air fuel ratio distribution
- ➔ Flow bench to measure and modify swirl and tumble ratio on the new LDB engine

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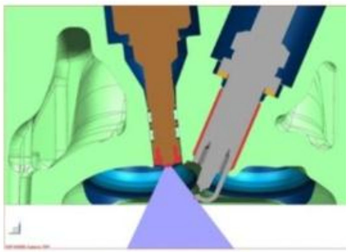
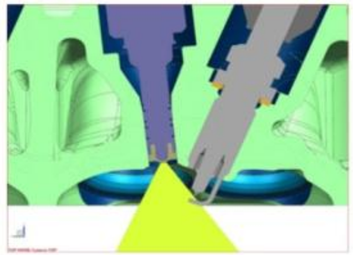
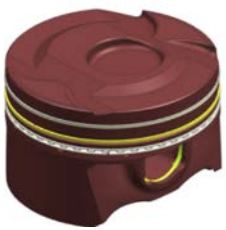
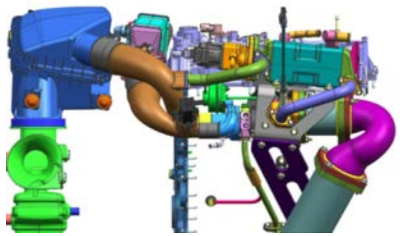
Accomplishments – Phase 3: 1.4L LDB Engine Combustion Features

1.4L Boosted Stoich	1.4L LDB	
		✓ Fuel spray cone is targeted to the spark gap w/close-space injections ✓ Injector is pulled upward and spark plug is moved downward
		✓ LE2 piston bowl is modified to match SG5 NA piston bowl ✓ Piston crown is modified to result in 10.5 compression ratio
		✓ Added low pressure cooled EGR system ✓ Moved TWC catalyst location for meeting T2B2 HC emission level

➔ Start with 1.4L boosted stoichiometric-homogeneous combustion engine

➔ Modifications made to engine components to enable lean-stratified operation

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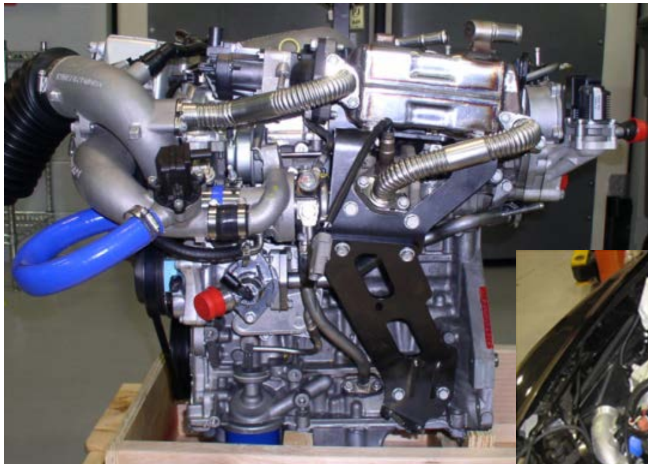
Accomplishments – Phase 3: LDB Engine Procured, Built & Installed



Charge & Exhaust System

- ✓ Compact turbocharger to support high EGR, low RPM performance
- ✓ Cooled low-pressure EGR with gases taken downstream of the turbo
- ✓ Air-to-water charge air cooler with independent low temperature coolant circuit & auxiliary pump
- ✓ Close Coupled TWC Catalyst integrated in turbine housing

➔ Four 1.4L Lean Downsize Boost (LDB) engines are designed, procured and built to support calibration, controls development, integration and fuel economy optimization

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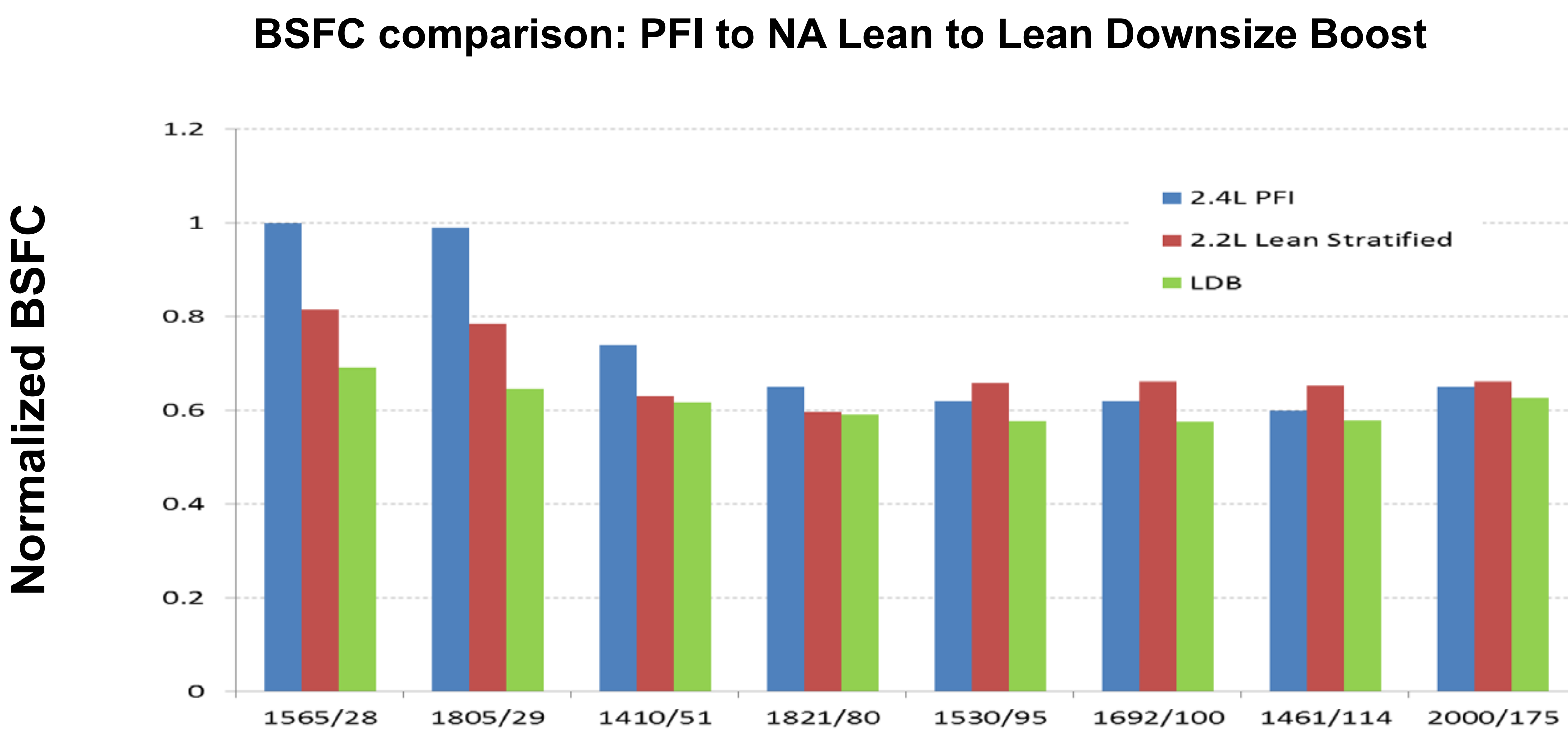
Accomplishments – Phase 3: LDB Boosted Lean Combustion



- ➔ The LDB engine delivers ~15% improvement in fuel consumption at 25 to 30 Nm
- ➔ The SG5 naturally aspirated engine lean stratified operation limit is ~85 Nm
- ➔ The LDB engine lean stratified operation limit is ~120 Nm, results in ~7% improvement in fuel consumption

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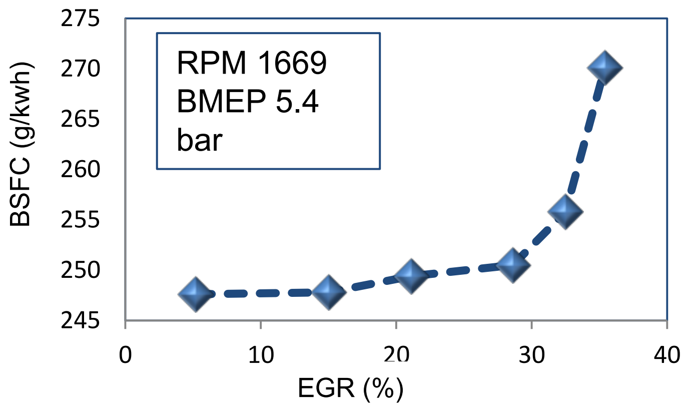
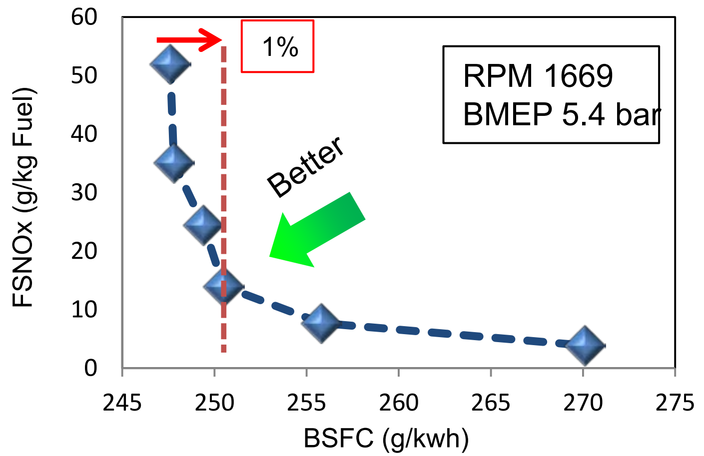
Accomplishments – Phase 3: LDB Engine BSFC vs FSNOx Trade-off

Lean Downsize Boost Engine Calibration Strategy:

- ✓ When the engine is running lean, small amount of EGR will not have significant impact on BSFC
- ✓ Small amount of EGR will have significant impact on engine-out NOx emission
- ✓ One percent BSFC degradation point is selected to represent the best trade-off calibration point





➔ Cooled EGR is added to reduce NOx emission until 1% BSFC degradation is observed

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Accomplishments – Phase 3: Vehicle Fuel Economy Projections

Targeted Efficiency Improvement

- ✓ Downsizing 7-8 %
- ✓ Dilute & Lean Combustion 12-13%
- ✓ Total from Engine 19-21 %

- ✓ 12V Stop/Start & Active Thermal Management 5 %

FE Projections: PFI to NA Lean to Lean Downsize Boost

				BSFC Improvement	
		Speed (RPM)	Load (n-m)	PFI to Lean NA	PFI to LDB
Urban	Idle	700	19	0%	0%
	Zone 2	1335	27	17%	30%
	Zone 3	1565	28	19%	31%
	Zone 4	1805	29	18%	35%
	Zone 5	1530	95	-1%	7%
	Zone 6	1821	80	3%	9%
	Zone 7	2250	101	0%	7%
Highway	Zone 8	1410	51	18%	16%
	Zone 9	1669	60	9%	14%
	Zone 10	1461	114	0%	3%
	Zone 11	1692	100	0%	6%

	Projected FE Improvement	
City	12%	26%
Highway	8%	12%
Combined	10%	21%

➔ The LDB engine in combination with 12V Stop/Start and Active Thermal Management is projected to meet the 25% fuel economy improvement target

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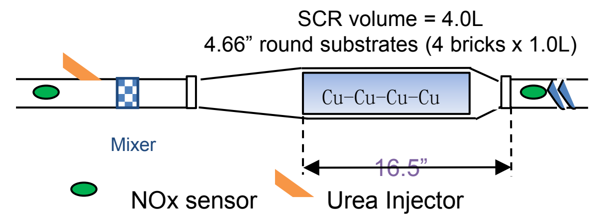
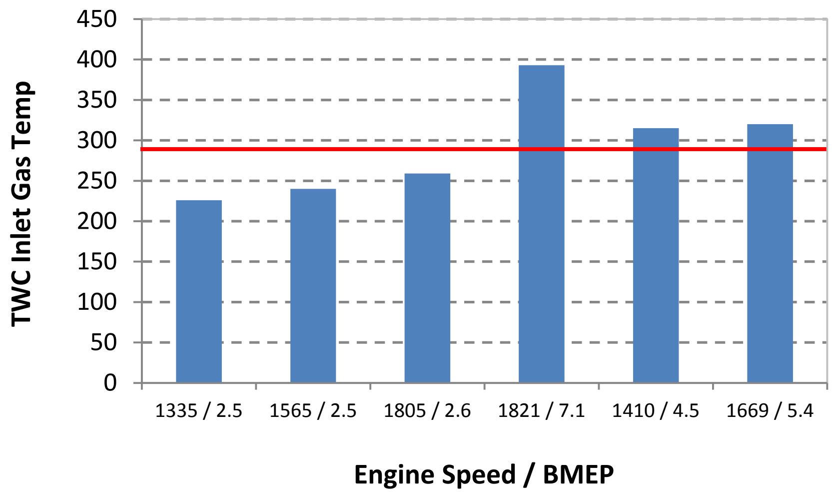
Accomplishments – Phase 3: Passive/Active Ammonia SCR System

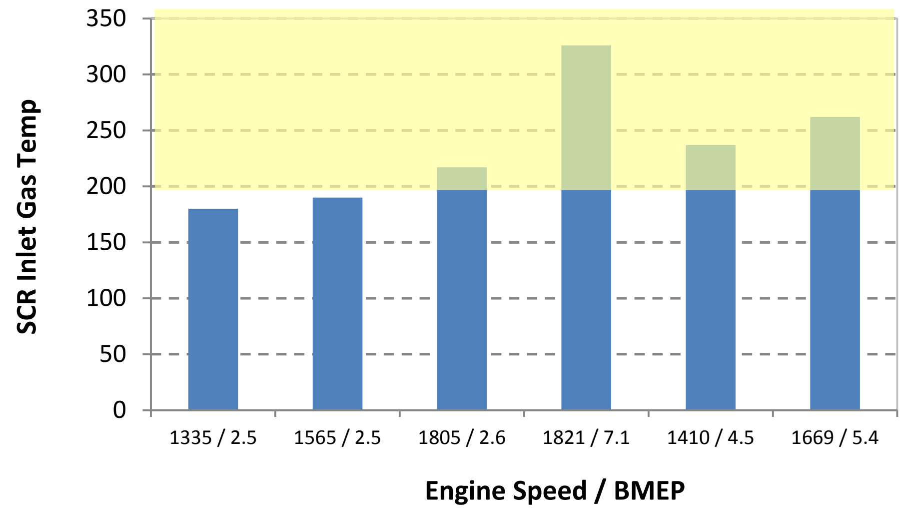
Passive/Active SCR – LDB 1.4L Boosted

✓ Apply as much as possible of the SG5 exhaust architecture on LDB engine.



Engine Dyno Data





➔ Exhaust gas temperature into the catalyst is much lower than the SG5 (leaner AFR and turbo impact)

➔ TWC light-off temperature may be a challenge and require enrichment (FE effects unknown)

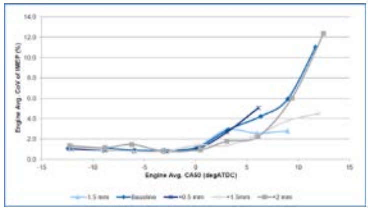
➔ SCR technology will start with copper zeolite which historically performs well at lower temperature

Lean Gasoline System Development
Collaboration – Key Supplier Involvement

The program is partnering with the following suppliers in order to develop a common understanding of the integration challenges to implement lean gasoline systems in to production

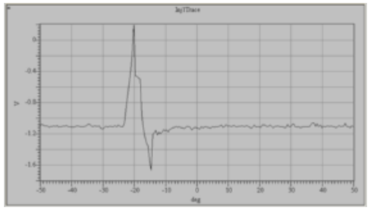
RICARDO

Calibration and combustion performance evaluation of lean gasoline combustion technology enablers



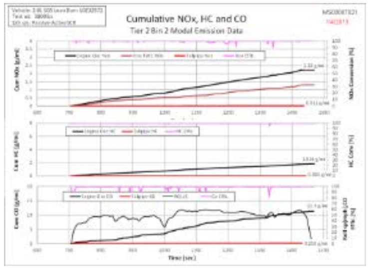
BOSCH

Fuel injector to enable multiple close-spaced injection capability



umicore

Aftertreatment hardware formulations supporting passive and active ammonia systems integration



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Future Work – Remainder of FY13 and Project

Calibrate

- 1.4L LDB engine fuel economy enhancing features

Integrate

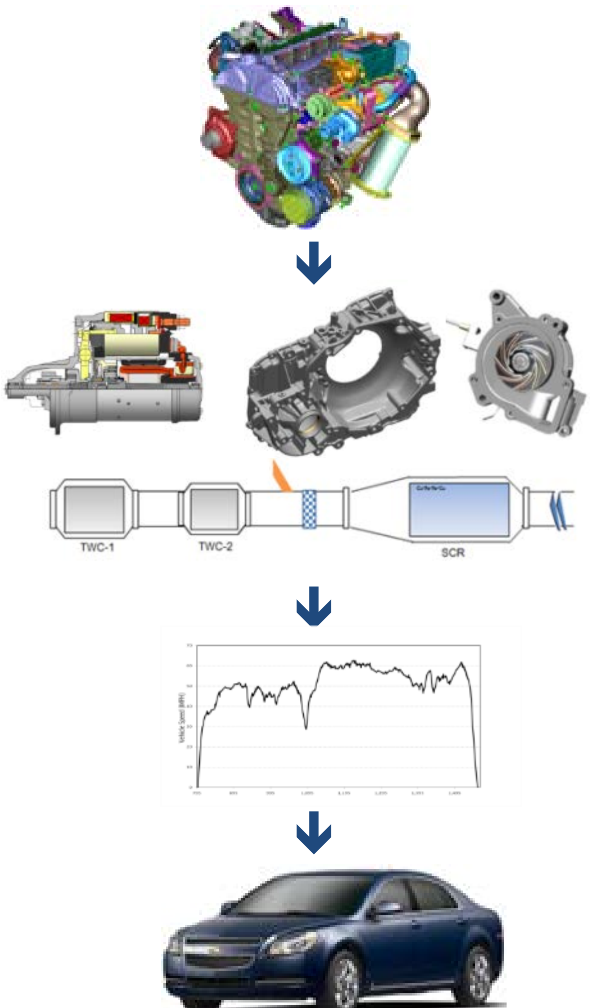
- LDB engine
- 12V Stop/Start
- Active Thermal Management system
- Passive/Active Ammonia SCR System (PAASS)

Optimize

- Lean boosted controls & calibration for drivability

Demo

- Demonstrate fuel economy & T2B2 emissions



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Summary – FY12 to FY13

Phase 2 – Complete

- ✓ SG5 NA engine utilized in vehicle to develop engine and aftertreatment controls along with utilizing as a lean combustion emissions generator
- ✓ Passive and Active aftertreatment systems have been combined to provide the optimal lean gasoline aftertreatment system that minimizes urea consumption under all lean-stratified and stoichiometric-homogeneous operating conditions

Phase 3 (the last one) – In process, final system optimization

- ✓ 4 Lean Downsize Boost (LDB) engines have been designed, procured & built
- ✓ LDB engine calibration has supported optimization of the BSFC performance
- ✓ LDB engine, 12V Stop/Start, Active Thermal Management and Gen 4 PAASS aftertreatment systems are installed in a Malibu development vehicle
- ✓ Expect to meet FE and Emissions target

Timeline	Evaluation Milestone (1)	Evaluation Milestone (2)
12/23/11	Cold ftp & H FE > 13% - simulated	Gen 2 A/T dyno results – achieved
12/21/12	C & H FE > 20% - projected	Emissions < 150% w/PM - achieved
FY13 Goal	C & H FE > 25%	Emissions T2B2